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SUPPLEMENTARY DIELECTRIC-CONSTANT AND LOSS MEASUREMENTS ON HIGH-TEMPERATURE MATERIALS

J. Iglesias, et al

Massachusetts Institute of Technology
Cambridge, Massachusetts

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Laboratory for Insulation Research
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Abstract: This is a summary report on dielectric constant and loss measurements made in this laboratory after 1958, excepting high-dielectric-constant materials. The emphasis is on high-temperature materials (those with melting points above 1200°C), but data on some plastics and liquids are also included. The samples of solids include oxides of Al, Be, Cr, Hf, Mg, Si, Ta, Th, Y, Zr, nitrides of B and Si, $LaAlO_3$ and various silicates, rocks, and minerals. Pure samples of Al_2O_3, BeO, MgO, SiO_2, and BN all show loss tangents < 0.01 at 1500°C in the microwave region. Various phenomena of electric loss, e.g., transconductance, dipole orientation, and molecular vibrations are clearly discernible. A fundamental analysis will be undertaken in connection with our over-all research program on dielectric spectroscopy.

General Properties

The obvious prime requisites for any high-temperature solid insulator are high melting point and wide optical-energy gap. The first parameter for most of the elements and compounds of interest is known and available in physics handbooks. The optical-energy gap refers to the one-electron band model and is the energy required to excite an electron into the conduction band.[1)] These ultraviolet absorption data are incomplete. Electrical conduction is often greatly enhanced by impurities and in some materials predominantly ionic; in practice the optical-energy-gap data are only a very rough guide. As has been previously pointed out,[2)] electrical losses in the microwave region in pure materials are due to infrared absorption spectra as well as charge transfer. Materials with impurities show increased losses in three ways: (1) increased conduction, i.e., charge transfer; (2) dipole relaxation losses; (3) broadened infrared spectra. The general appearance of the electrical spectra is illustrated in Fig. 1; in practice the individual loss regions may overlap considerably.

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1) Technical Report 191, Laboratory for Insulation Research, Massachusetts Institute of Technology, Cambridge, Mass., July, 1964.

2) Summary Technical Report No. 1 (AFML-TR-65-396), November, 1965, Laboratory for Insulation Research, Massachusetts Institute of Technology, Cambridge, Mass.

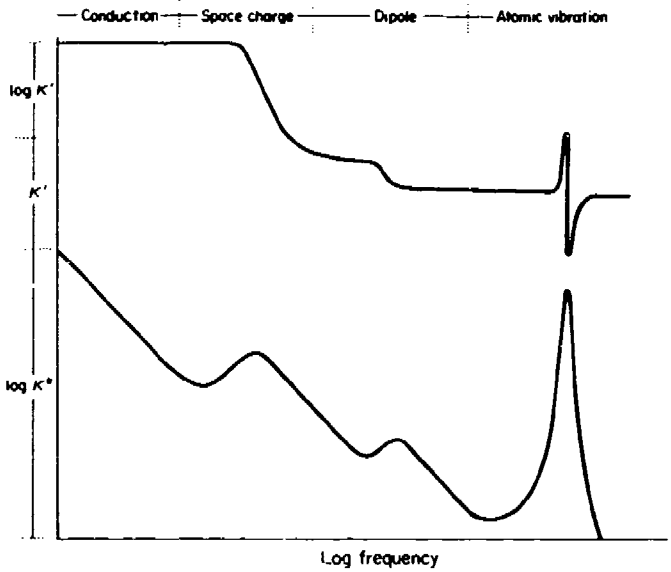

Fig. 1.
Dielectric spectra.

Melting Points

A discussion of the factors influencing the melting points of the elements and some of the binary compounds has been given previously.[1] As there is only one insulating element for high temperatures (diamond), most of the materials of interest are diatomic. The largest category are the oxides; their melting points are arranged according to the periodic chemical table (Table 1). About 25 of these are known to have melting points above 1600°C. The heavy atoms, in general supply many electrons for conduction at moderate temperatures. All known borides, carbides, halides, nitrides, silicides, and sulfides, with the exception of those listed in Table 2, have melting points (or decompose rapidly) below 1600° or are known to exhibit high conduction. Table 2 also lists compounds with 3 or 4 elements which have high melting points. The 25 high-temperature oxides of Table 1 and compounds listed in Table 2 comprise the present chemical list of compounds worthy of consideration. If the temperature limit is raised to 2000°C and the heavy and multivalent atoms are eliminated, the list reduces to C, BeO, MgO, Al_2O_3, CaO, Sc_2O_3, ZnO, SrO, Ca_2SiO_4, $MgAl_2O_4$, Be_3N_2, BN, AlN, Si_3N_4.

Measurement Techniques

When only small samples were available, two-terminal measurements were made in the lumped-circuit range, 10^2 to 10^7 Hz, using a laboratory-built bridge.[3]

3) Tech. Rep. 201, R. E. Charles, K. V. Rao, and W. B. Westphal, Lab. Ins. Res., Mass. Inst. Tech., Cambridge, Mass., October, 1966.

Table 1. Melting points of oxides in degrees centigrade.

Li >1700	Be 2530	B 460	C -566	N -908	O -192 O_3	F -			
Na 1275s	Mg 2800	Al 2015	Si 1713	P 580	S d70 - 95	Cl -			
K 490	Ca 2580	Sc -	Ti 1830 Ti_2O_3 2130	V 1970	Cr 2435	Mn 1705	Fe 1565	Co 1935	Ni 1990
Cu 1326	Zn 1975	Ga 1900	Ge 1115	As 193	Se 350s	Br -			
Rb 570	Sr 2430	Y 2410	Zr 2715	Nb 1780	Mo 795	Tc -	Ru 255	Rh d1100	Pd 870
Ag d300	Cd d900	In V850	Sn 1127	Sb 656	Te 733	I -			
Cs 490	Ba 1923	La 2315	Hf 2812	Ta 1800	W 1500	Re d1000	Os 500	Ir d1100	Pt d550
Au -	Hg d500	Tl 717	Pb 888	Bi 860	Po -	At -			
Fr -	Ra -	Ac -							
Ce 2600	Pr -	Nd 1900	Pm -	Sm -	Eu -	Gd Tb Dy Ho Er Tm Yb Lu - - 2340 - - - - -			
Th 3050	Pa -	U 2500	Np -						

s = sublimes; d = decomposes.

For larger samples three-terminal measurements could be made, and microwave measurements were performed using the standing-wave method with shorted-line and dielectric-filled resonant cavities.[3)] Materials that are very sensitive to atmosphere are noted in the data section, and more than one set of data is given. The microwave measurements with Pt-foil covered dielectrics are relatively free from atmospheric or diffusion effects. The highest temperature reached was about 1700°C.

Table 2. Binary tri-element compounds.

Tri-element	Melting point (°/C)	Binary	Melting point (°/C)
$BeAl_2O_3$	1870	CdS	1750 (100 A)
$CaAl_2O_4$	1600	HfN	3305
$CaCr_2O_4$	2090	MgS	d > 2000
$Ca_3(PO_4)_2$	1670	Mo_2C	2687
Ca_2SiO_4	2130	SiO	> 1702
$CaZrO_3$	2550	SrS	> 2000
$LiAlO_2$	1600	ThC_2	2655
(or $Li_2Al_2O_4$)		UB_2	2365
$MgAl_2O_4$	2135		
Mg_2SiO_4	1910		
$KAlSiO_4$	ca. 1800		
$SrSiO_4$	> 1750		
$SrSO_4$	1605		

Materials Measured and Their General Characteristics

The frequency characteristics of all materials measured under this program show common trends. The dielectric constant κ' (relative to vacuum) increases at low frequencies with high temperatures. The loss factor κ'' at high temperatures decreases with increasing frequency but seldom is proportional to 1/f. The slower change implies that the conductivity σ ($= \omega\kappa''\epsilon_0$) rises with frequency. Plots of log σ vs. the reciprocal of absolute temperature show deviations from the straight line given by the relation

$$\sigma = \sigma_o \, e^{-A/kT} .$$

The microwave temperature runs show the loss tangent steadily rising with temperature except for Brush B-6 beryllia and Carborundum alumina. These have sharp absorptions which look like vibration spectra. Exact interpretation will depend on data taken versus frequency at fixed temperature (given in the Index to the data).

Wide-Band Spectra. The dielectric spectrum of elemental insulators (we need consider only carbon in diamond form) consists ideally of two parts: low-frequency conduction loss due to thermal excitation of electrons from the valence to conduction band and electronic vibration spectrum in the ultraviolet region. In the microwave region conduction losses should predominate; we estimate that the loss tangent should reach 0.01 at about 2100°C.[4] No data are available to indicate if best crystals approach the ideal, a strongly bonded material (m.p. > 3500°C) with large energy gap (5 to 7 eV).

The cubic diatomic insulators - MgO is the best example - ideally show only three regions of loss. The vibration spectrum of the magnesium-oxygen bond is added to low-frequency conduction loss and electronic ultraviolet spectrum. The optical energy gap of MgO is 8.7 eV. Measurements of conductivity show much lower gaps (2 to 4.6 eV), partly because of impurities and partly because of vacancies existing at high temperatures.

We have data in the far infrared on SrF_2 indicating agreement between extrapolated vibration loss and microwave data (p. 62).

The heavy diatomic insulators - thorium oxide is a cubic example - have strong bonds with many electrons (m.p. = 3000°C), but only moderate temperatures are needed to excite electrons for conduction. Our data on a technical grade ThO_2 ceramic show appreciable conduction at 500°C and a dipolar response at lower temperatures.

The noncubic materials have more than one infrared vibration mode. The reflectivity of hexagonal Al_2O_3 shows a complicated response with high losses over the region 8 to 30 μ (1 to 3.8×10^{13} Hz). Optical data indicate a band gap of above 8 eV at 25°, decreasing to about 6.9 eV at 900°C. Conductivity data indicate much lower activation energies, probably due to oxygen vacancies and ready acceptance by the lattice of many metallic impurities.

Another hexagonal oxide, BeO in ceramic form, has recently been measured in this laboratory[5] and shows very low high-temperature conductivity in agreement with the reported statement that BeO exhibits lower conductivity than any other

---

4) Based on the one-electron model, see Ref. 1, pp. 20 and 21, and no change in energy gap with temperature. Measurements on Ge show appreciable reduction gap with temperature.

5) Summary Tech. Rep. No. 1 (AFML-TR-65-396), Lab. Ins. Res., Mass. Inst. Tech., Cambridge, Mass., November, 1965, pp. 18, 19.

oxide.[6)]

The heavy noncubic oxides all exhibit high conduction at 500°C.[7)]

High-purity yttria[8)] shows lower losses than previously reported for a single crystal;[9)] losses to 500°C are comparable with those of high-purity alumina.

Nitrides of B, Al, Si, and Mg_2S are of interest for high-temperature work. Data on a commercial ceramic and pyrolytic material of S_3N_4 have been published previously.[10)]

<u>Summary</u>. Pure oxides of alumina, beryllium, magnesium, and silicon have electrical properties suitable for microwave windows to at least 1500°C. Boron nitride is also suitable and has considerably lower temperature coefficient of dielectric constant. While the dominating microwave loss process is conduction in low-purity materials, the infrared absorptions are also important.

Dielectric Data

The following pages of data list materials as inorganic or organic. The first section is arranged alphabetically according to chemical name. The organics are listed alphabetically according to manufacturer or supplier. The data show permittivity relative to vacuum κ' or ϵ'/ϵ_o; dielectric loss factor κ'' or ϵ''/ϵ_o; loss tangent, tan δ, a. c. conductivity σ in ohm-cm $^{-1}$ or a. c. resistivity ρ in ohm-cm. The magnetic parameters shown are the permeability relative to vacuum κ'_m or μ'/μ_o, magnetic loss factor κ''_m or μ''/μ_o, and magnetic loss tangent tan δ_m. Refer to Tech. Rep. 189 for conversion to other parameters such as attenuation factor, propagation constant, intrinsic impedance, etc.[11)]

In the index are listed many materials measured in our laboratory since 1958. Data already given in our technical reports are not repeated, but references are given. The index also lists the temperature (T°C) at which the microwave loss tangent reached 0.01 in our measurements.

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6) E. Ryshkewitch, "Oxide Ceramics," Academic Press, New York and London, 1960, p. 330.

7) Ref. 5, p. 24.

8) Ref. 5, p. 25.

9) W. B. Westphal, Tech. Rep. 182, Lab. Ins. Res., Mass. Inst. Tech., October, 1963.

10) Ref. 5, pp. 26, 27.

11) Tech. Rep. 189, Lab. Ins. Res., Mass. Inst. Tech., May, 1964.

I. INORGANIC COMPOUNDS

	T°C	T.R. 182	Summary T.R. 1	T.R.203
Aluminum nitride				
AlN, hexagonal, MP > 2200 (in N_2)				
Carborundum, hot-pressed	670			15
Aluminum oxide				
Al_2O_3, hexagonal, MP 2050°C				
Single crystal				
Linde		24, 25		
Multicrystalline				
Alberox A-950	892			15
A-962	820	45		
American Lava 576	1050	45		
614	1035	45		
719	960	45		
Armour Research, density = 3. 32				16, 17
E-11				18, 19
E-20				20
A-76				21 - 23
A-75				24 - 26
mixtures				27
Carborundum 1542	1085	46		
Centralab 205				28
206				28
Coors AD-99	1300	46		
AD-995	~1500	46		
MC-2014	-	46		
RR	800	47		
Coors-NBS 10F2	800			28
Diamonite B-890-2	960	47		
P-3662	975	47		
Frenchtown 7225				28
General Electric Lucalox (1965)	365	29, 48		
" " " (1960)	1000			29
Interntl. Pipe & Ceramic V-69				29
" " " TC-301				
" " " TC-302-H	~900			29
" " " TC-351	~1000			30

Aluminum oxide (cont.)	$T^{o}C$	T.R. 182	Summary T.R. 1	T.R. 203
Minneapolis Honeywell A-127	930	48		
A-203	810	48		
National Beryllia Alox	1170	48		
Norton 99.5%	1300	49		
Raytheon	-			30
Steatit-Mag A.G. A-18	-	49		31
U.S. Stoneware 610	1230	49		
A-212	1235	49		
A-216	665	50		
A-312	675	50		
Std. $3050^{o}F$	955	50		
Western Gold Platinum AL-300	1100	50		
Modified AL-300				32
AL-400	1030	51		
AL-500				32
AL-995	1280	51		
AL-1009	1390	51		
Barium fluoride				
BaF_2, cubic, m.p. $1280^{o}C$				
Single crystal				
M.I.T., Crystal Phys. Lab.	-			33, 34
Beryllium oxide				
Single crystal, hexagonal, m.p. 2530				
Electronic Space Products				34
Multicrystalline				
American Lava 754	-	-		34
Brush B-6	1060			
B-7-6	1320			
B-7-37	1320			
F-1	1420			
Coors BD-98	-	-		34
National Beryllia, cold-pressed	1190			
Berlox	-	-		34
with silicon carbide, see SiC				
North American translucent			18, 19	
Beryllium orthosilicate (Be_2SiO_4), trigonal				
Single crystal				
Electronic Space Products				35

	T $^{\circ}$C	T. R. 182	Summary T. R. 1	T. R. 203
Bismuth silicate				35
Boron nitride, hexagonal, 3000 $^{\circ}$C sublimes				36
Carborundum, hot-pressed	1130	53		
High-Temperature Materials, pyrolytic		31		37
National Carbon, hot-pressed HBN	1400			38
" " " HD-0056	-			39
" " " HD-0086	940			39
Raytheon, pyrolytic	1740			40
Calcium carbonate				
Single crystal mineral (Calcite), hexagonal, decomposes at 894 $^{\circ}$C				41
Calcium fluoride				
Single crystal, cubic, m.p. 1360 $^{\circ}$C				
M. I. T., Crystal Physics Laboratory				42
M. I. T., Ceramics Laboratory				43
Cerium fluoride, m.p. 1460 $^{\circ}$C				
Ceramic, M.I.T., Lab. Ins. Res.				44
Chromium oxide				
Single crystal, hexagonal, m.p. 1990 $^{\circ}$C				
Linde		32		
Cobalt oxide				
Single crystal, cubic, m.p. 1935 $^{\circ}$C				
M. I. T., Crystal Physics Lab.				44
Cobalt oxide/nickel oxide mixed crystal,				
M. I. T., Crystal Physics Lab.				44
Copper halides, m.p. 430 $^{\circ}$-605 $^{\circ}$C				
Pressed-powder, M. I. T., Lab. Ins. Res.				44
Hafnium oxide, cubic, m.p. 2810 $^{\circ}$C				
Multicrystalline				
Zircoa			20, 24	
Hydrogen oxide, glacial, ices, see Sec. II				
Lanthanum aluminate, m.p. 1612 $^{\circ}$C				
Single crystal				
National Lead		33		
Lead bromide, orthorhombic, m.p. 373 $^{\circ}$C				
Single crystal, M.I.T., Crystal Physics Lab., also see see Final Report under Contract Nonr-1841(88), March 11, 1965				45
Lead bromide/lead chloride mixed crystals, see above				45
Lead chloride				45

	$T^{\circ}C$	T.R. 182	Summary T.R. 1	T.R. 203
Magnesium-aluminum silicate (cordierite)				
Multicrystalline, Raytheon	T=550			45
Magnesium carbonate, d 350°				
Pressed powder				45
Magnesium oxide, cubic, m.p. 2800°C				
Multicrystalline				
Kodak Itran-5				46
M.I.T., Lab. Ins. Res.		34, 36		
Minneapolis Honeywell				
Magnesium metasilicate, steatite fired to clinoensteatite, monoclinic, decomposes at 1570°C				
Multicrystalline				
Bell Telephone Labs. F-66	T = 780			46
Internatl. Pipe & Ceramic TC 503				46
Magnesium orthosilicate (fosterite), orthorhombic, m.p. 1890°C				
Multicrystalline				
Steatite-Magnesia AG Frequenta M				47
Magnesium titanate, $MgTiO_3$				
Multicrystalline, U.S. Sonics				48
Magnesium fluoride, tetragonal, m.p. 856°C				
Single crystal, Columbia Univ.				49
Nickel oxide, cubic, m.p. 1990°C				49
Rubidium manganese fluoride, $RbMnF_3$				
Single crystal, cubic, m.p. 1050°C				
M.I.T., Materials Center				49
Silicon				
Single crystal, cubic, m.p. 1420°C, Brown Univ.				50
M.I.T., Crystal Physics Laboratory				50
Silicon carbide				
Multicrystalline				
Carborundum				51
With BeO				
National Beryllia Corp. Carberlox				52
Silicon dioxide				
Single crystal quartz mineral, hexagonal-cubic, m.p. 1710°C (Prog. Rep. No. XXXIV, L.I.R., p. 65)				52, 53

Silicon dioxide (cont.)	$T^{o}C$	T.R. 182	Summary T.R. 1	T.R. 203
Fort Monmouth				
Glasses (glass mica mixtures and glass ceramics, see Sec. II)				
American Optical Amersil, clear	T >1400	53		
" transpar.	T =1165	53		
Corning 7940	T >1500			54, 55
C. E. 101	T =1170	38, 39, 55		
Mixed Silicate glasses				
Corning Lab. No. 119BUC				55
Corning, Code 1723				55
Lancaster 7352				56
7357				56
L1957				57
L8100				58
Owens-Corning X 994				59
Pittsburgh Plate Glass, plate glass				59
" " " sheet glass				59
Silicon nitride, sublimes at 1900°C				
Pyrolytic, North American Res.			27	
Ceramic, Haynes Stellite			26	
Silver iodide				
Pressed powder, L.I.R.				60
Sodium chloride + $BiCl_3$, M.I.T., Crystal Physics Lab., see Quart. Prog. Rep. No. 8,				
Strontium fluoride, cubic, m.p. > 1450				
Single crystal, M.I.T., Crystal Physics Lab.				61, 62
Tantalum oxide, orthorhombic, decomposes at 1470°C				
Ceramic, Ciba powder, fired at L.I.R.		42		
Thallium bromide crystal, M.I.T., Crystal Physics Lab.				63
bromide-chloride cryst., ditto				63
bromide-iodide " "				63
Thallium chloride crystal				63
Thallium fluoride pressed powder				63
Thallium iodide, polycrystalline				63
Thorium oxide, cubic, m.p. 3050°C				
Ceramic, L.I.R., M.I.T.		40, 41		
Zircoa				

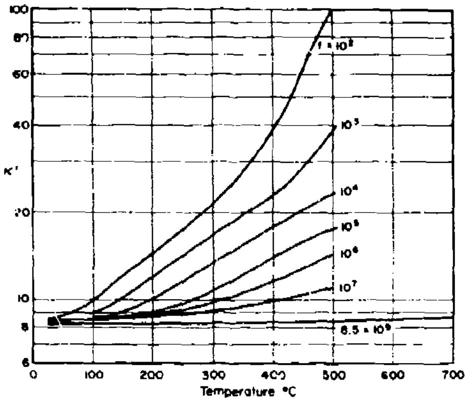
	$T^{o}C$	T.R. 182	Summary T.R. 1	T.R. 203
Vanadium oxide (V_2O_3), pressed powder				63
Yttrium oxide (Y_2O_3), m.p. 2410°C				
Single crystal, M.I.T., L.I.R.		43		
Ceramic, Zircoa			25	
Zinc oxide (ZnO), hexagonal, m.p. 1975°C				
Single crystal, Airtron Division, Litton Industries				63
Zirconium oxide (ZrO_2), mono.-cubic, m.p. 2715°C				
Ceramic Zircoa, tech. grade			21, 24	
" " nuclear grades			22-24	
"Zircolite", AFML				64
Zirconium silicate (zircon)				
Single crystal, mineral				65, 66, 67

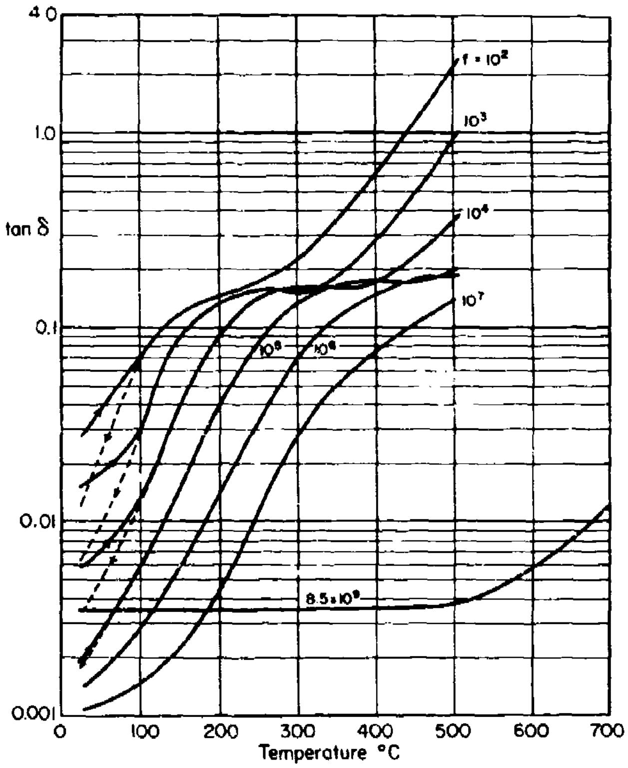
II. MINERALS, ROCKS, SOILS, MISCELLANEOUS INORGANICS

Single crystal minerals				
Apatite				68, 69
Astrophyllite				69
Benitoite				69
Beryl				70, 71
Calcite, see Sec. I				
Neptunite				71
Quartz, see Sec. I				
Spodumene				72, 73, 74
Topaz				75, 76
Tourmaline				76
Zircon, see Sec. I				
Crushed minerals				
Halite				77
Limonite				77
Magnesite				77
Quartz sand				77
Rocks				
Basalt, Hawaiian, dense				78
" " porous				78
Granite, Quincy				79
" Virginia				79

III. ORGANIC COMPOUNDS

Aluminum nitride, hot pressed
The Carborundum Co.

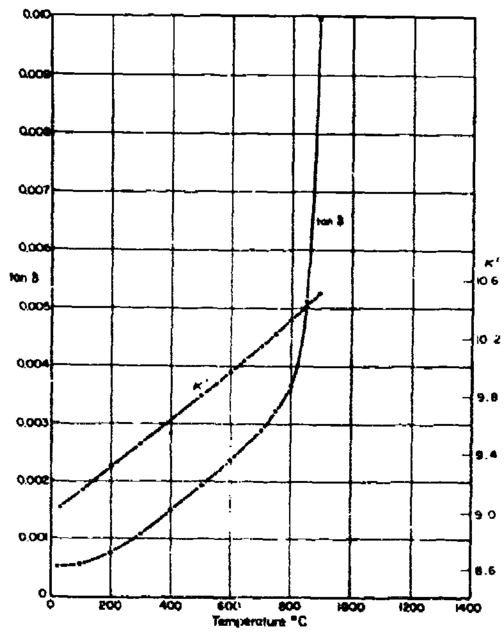




Aluminum oxide

Alberox Corp. A-950
3.663 g/cm^3

T^{o}C	κ'	tan δ
25	9.01	.00051
100	9.14	.00055
200	9.30	.00074
300	9.46	.00108
400	9.53	.00149
500	9.79	.00192
600	9.95	.00237
700	10.13	.00288
750	10.22	.00320
800	10.31	.00367
850	10.41	.0051
892	10.50	.010
3.89 - 3.61 GHz		
8.500 GHz		
25	8.98	.00058



Alumina, high-purity

Armour Research Foundation

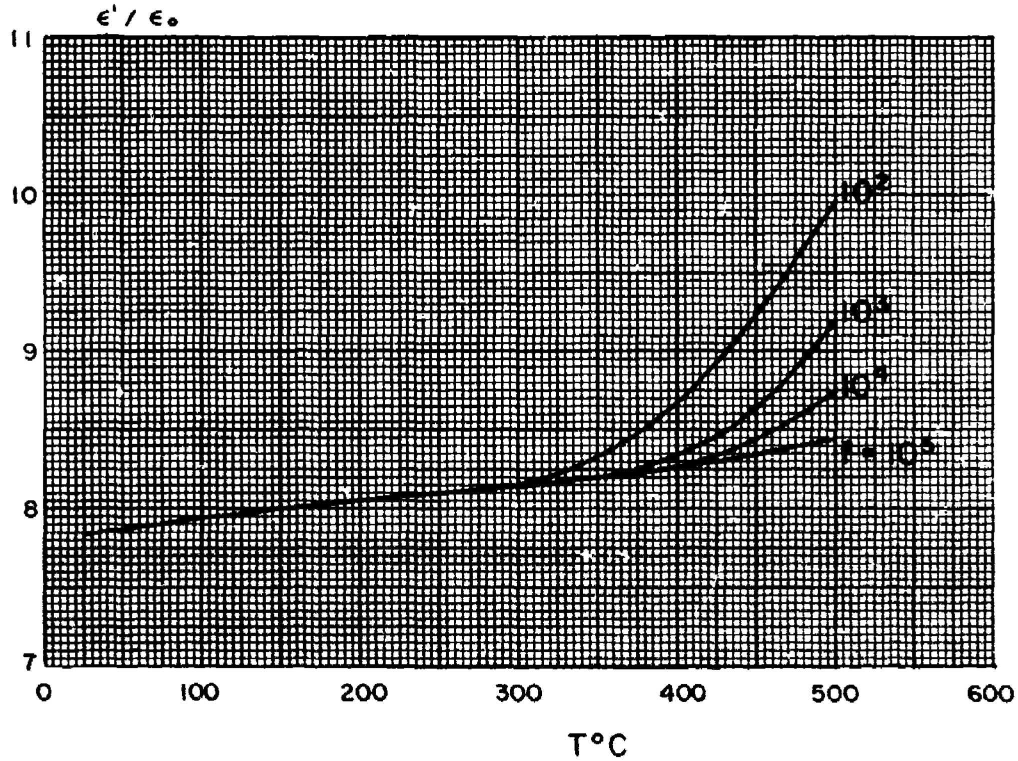
From Alcoa 99.99% Al with HF, fired air 1820°C

Spectrographic analysis: concentration of elements in parts per million:

Si	Mg	Fe	Ca	Cu
111	58	38	3	5

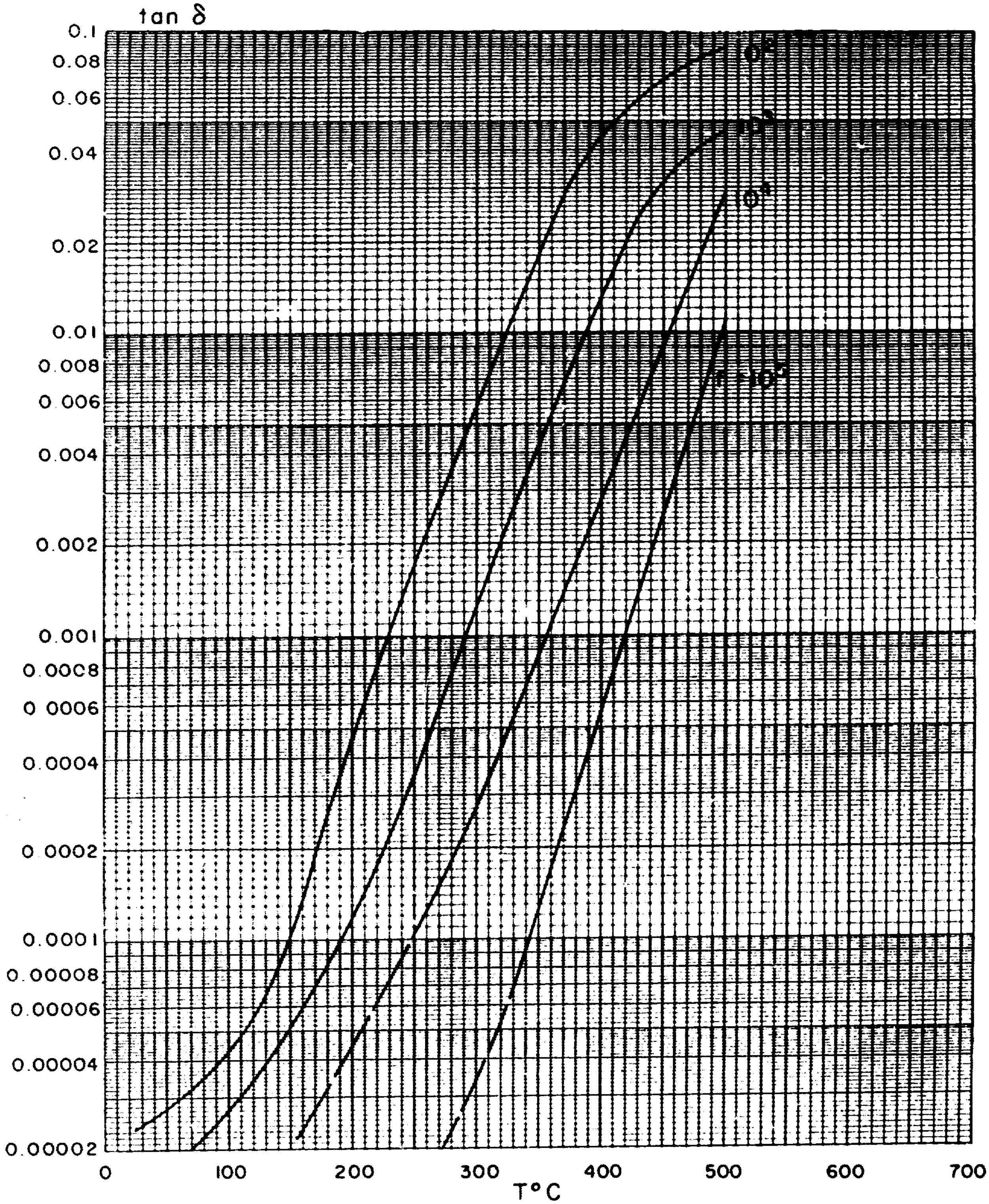
Density 3.32 g/cm^3

Fired silver electrodes



Alumina (cont.) Armour Research Foundation

Density 3.32



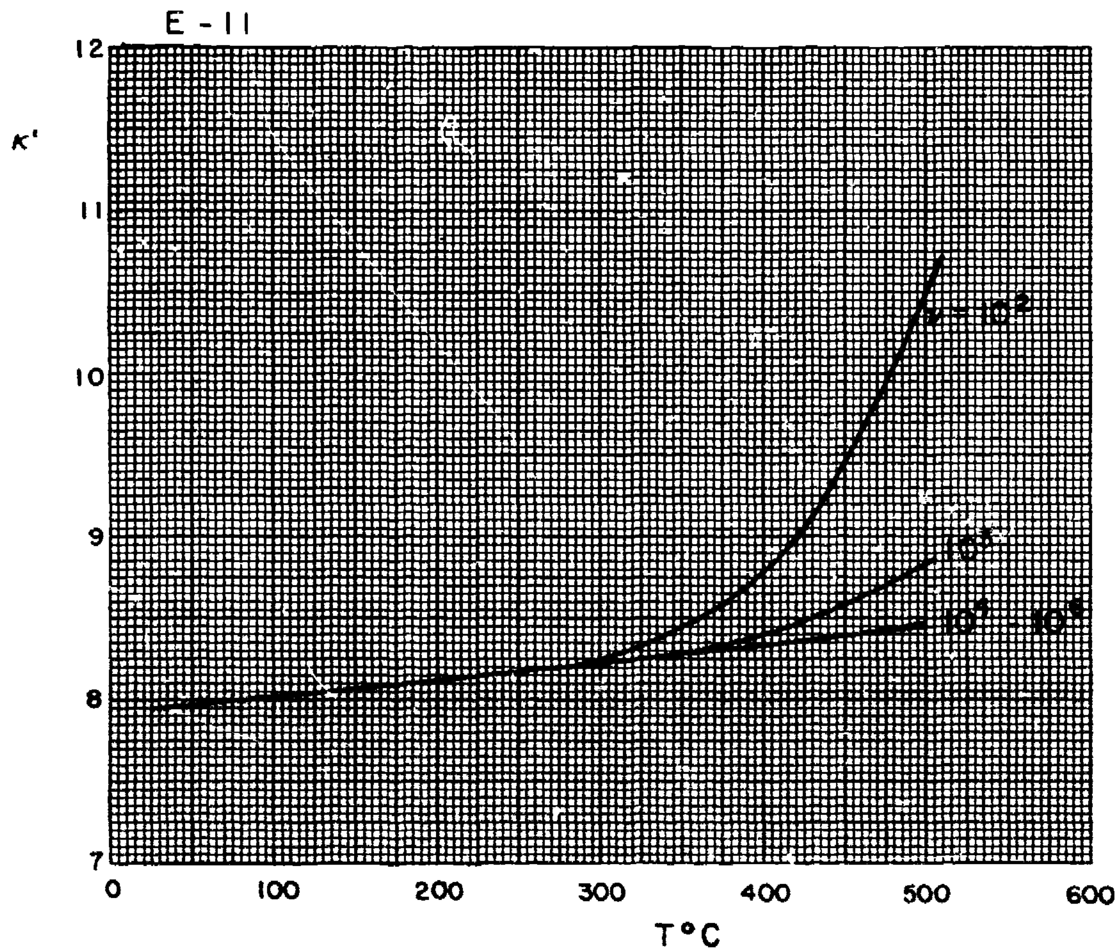
Alumina, high-purity — Armour Research Foundation

From Reynolds 99.999% Al with HF, fired air 1840°C

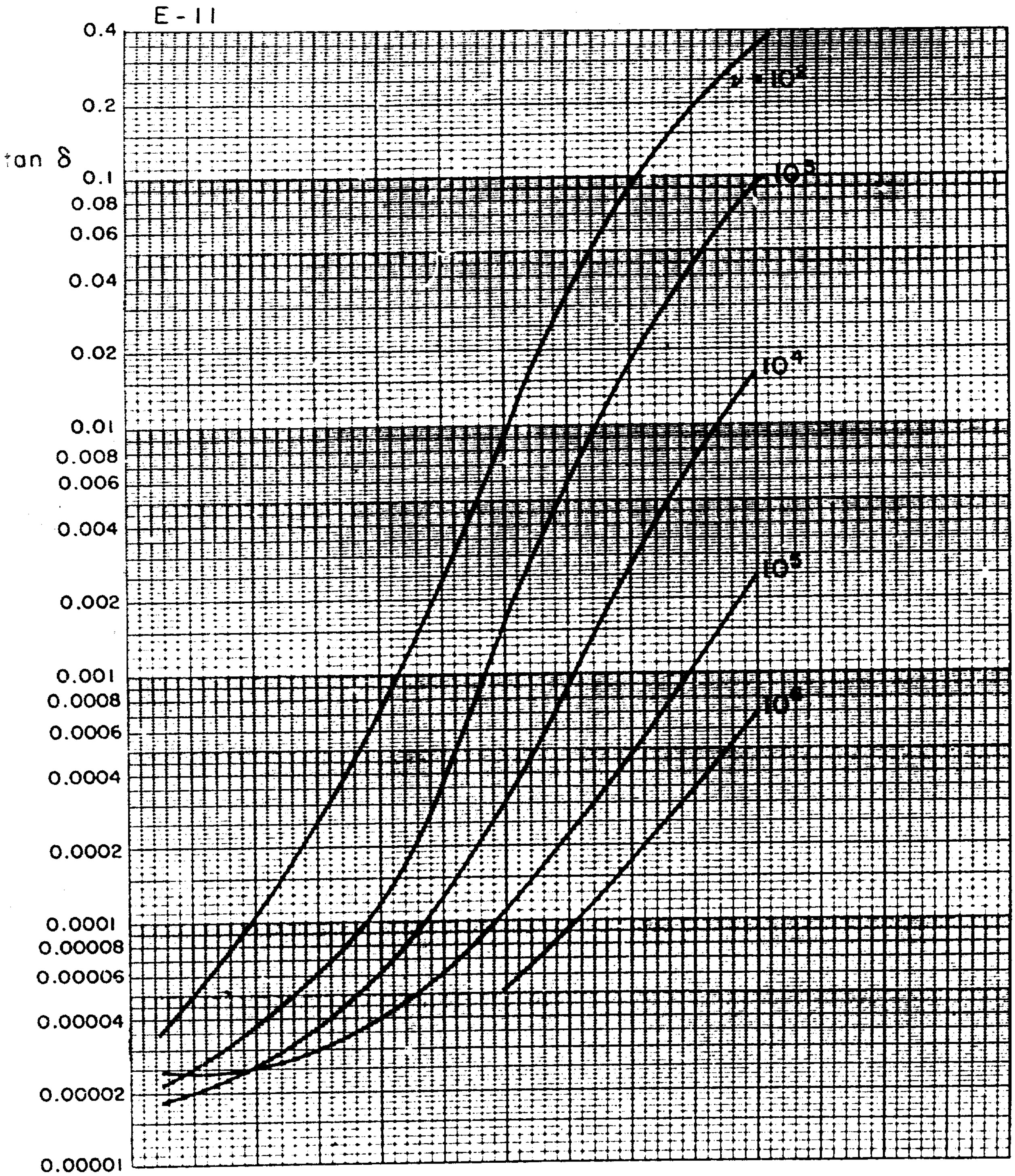
Spectrographic analysis: concentration of elements in parts per million:

Si	Mg	Fe	Ca	Ni	Cr	Cu
60	30	60	15	5	4	3

Density 3.23 g/cm^3

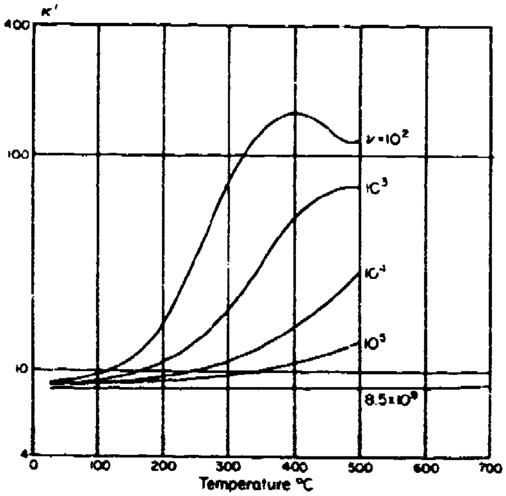


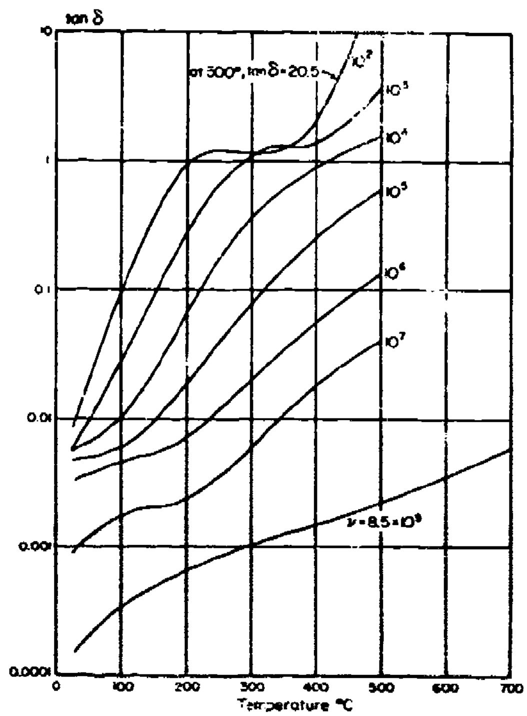
ν, frequency in Hz


E - 11
tan δ
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
0.008
0.006
0.004
0.002
0.001
0.0008
0.0006
0.0004
0.0002
0.0001
0.00008
0.00006
0.00004
0.00002
0.00001
ν = 10²
10³
10⁴
10⁵
10⁶

Alumina oxide with added silicic acid — **Armour Research Foundation**

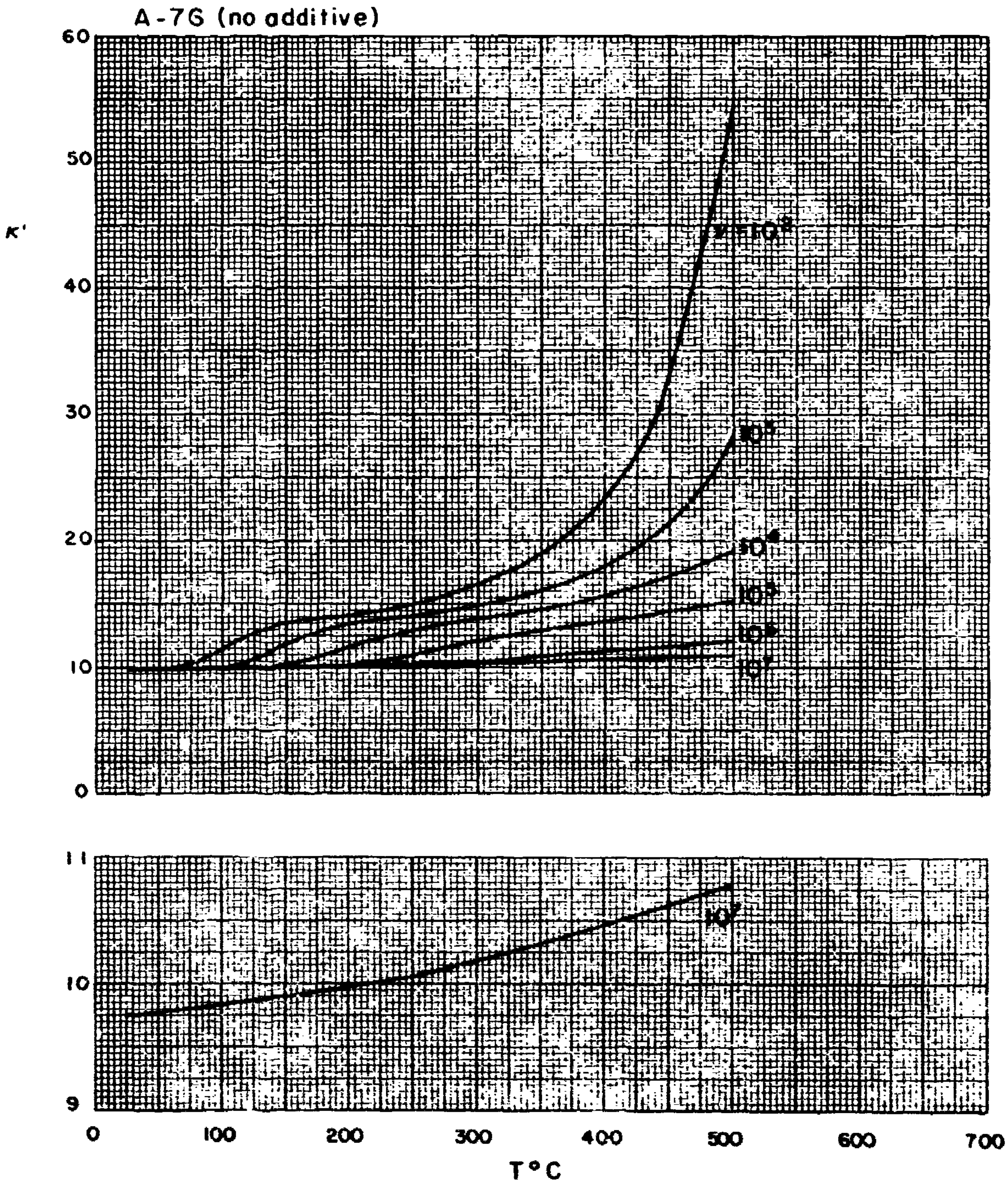
Fired air 1890°C
850 ppm Si, 550 ppm Na
Fired silver electrodes
Density 3.49 g/cm³

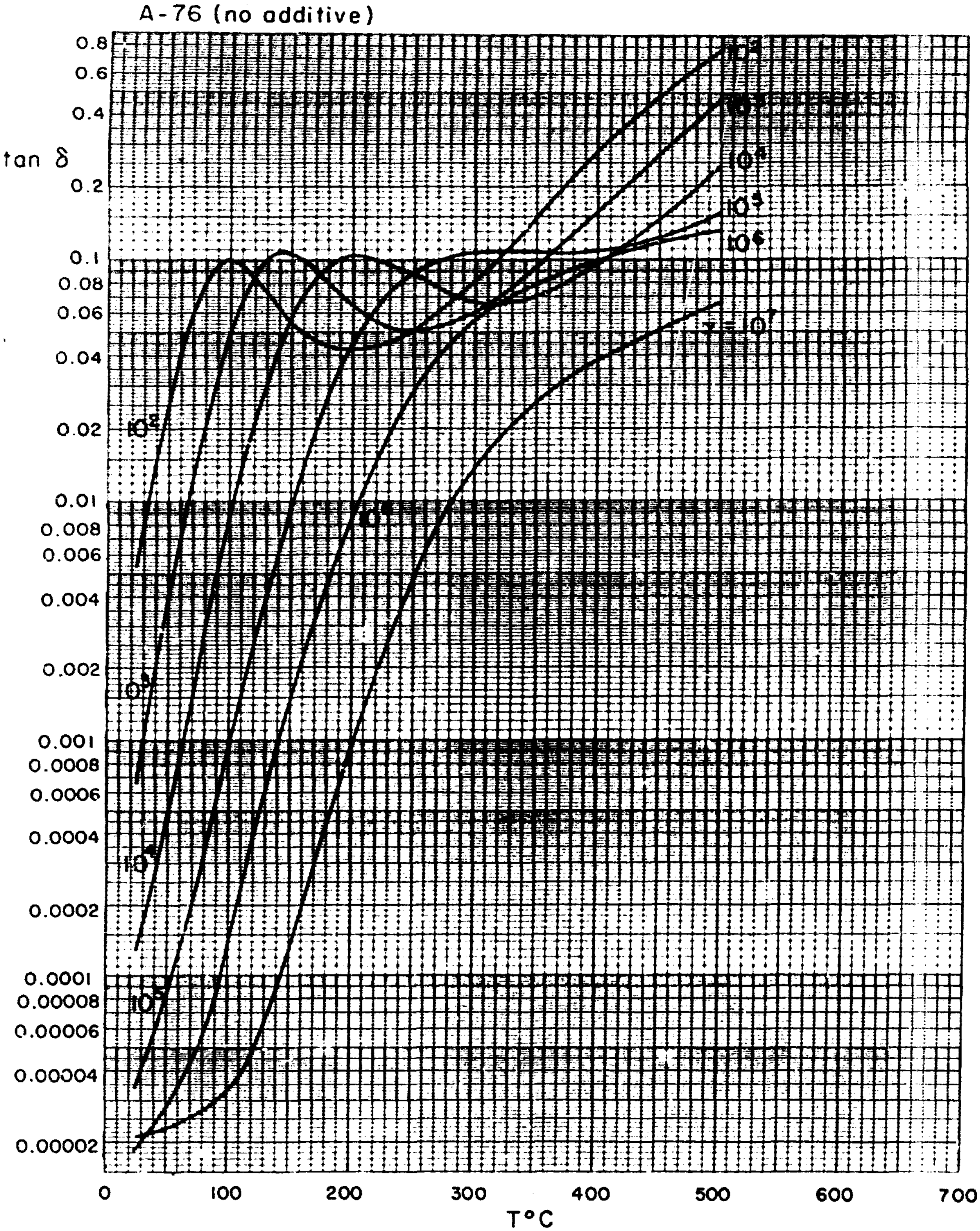




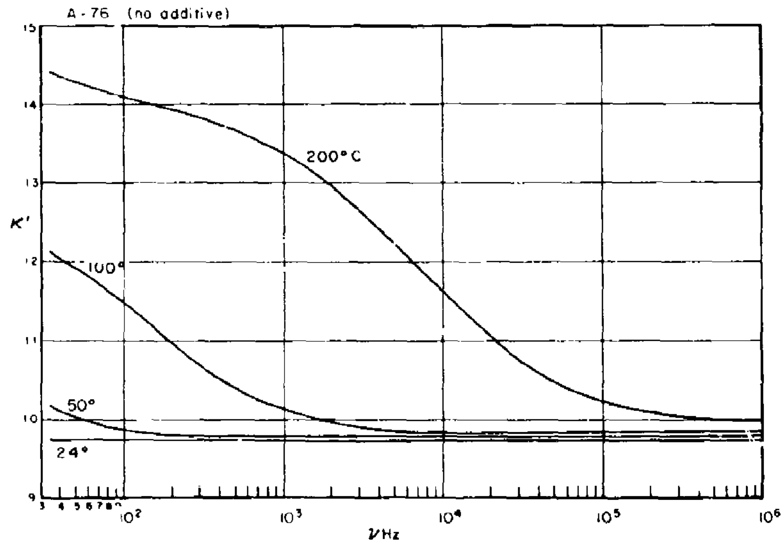
Alumina, high purity, hot-pressed in C — Armour Research Foundation

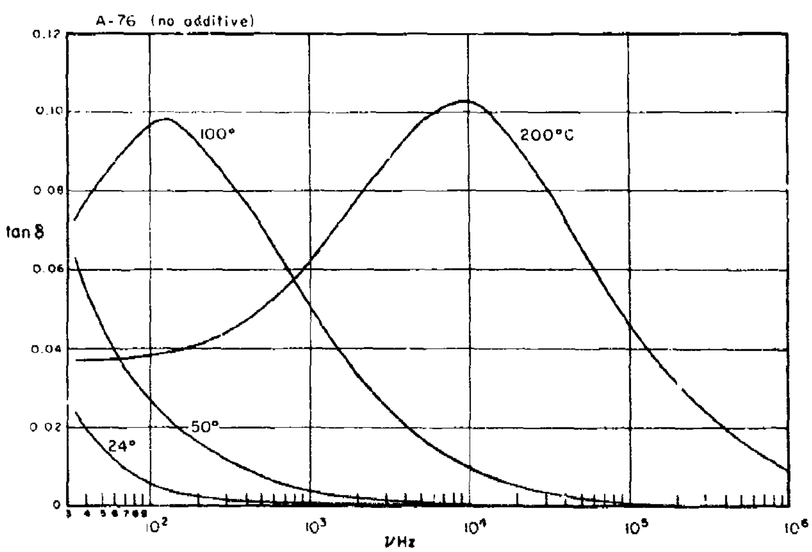
Density 3.84 g/cm^3




A-76 (no additive)
tan δ
0.8
0.6
0.4
0.2
0.1
0.08
0.06
0.04
0.02
0.01
0.008
0.006
0.004
0.002
0.001
0.0008
0.0006
0.0004
0.0002
0.0001
0.00008
0.00006
0.00004
0.00002
0
100
200
300
400
500
600
700
T°C
ν = 10⁷

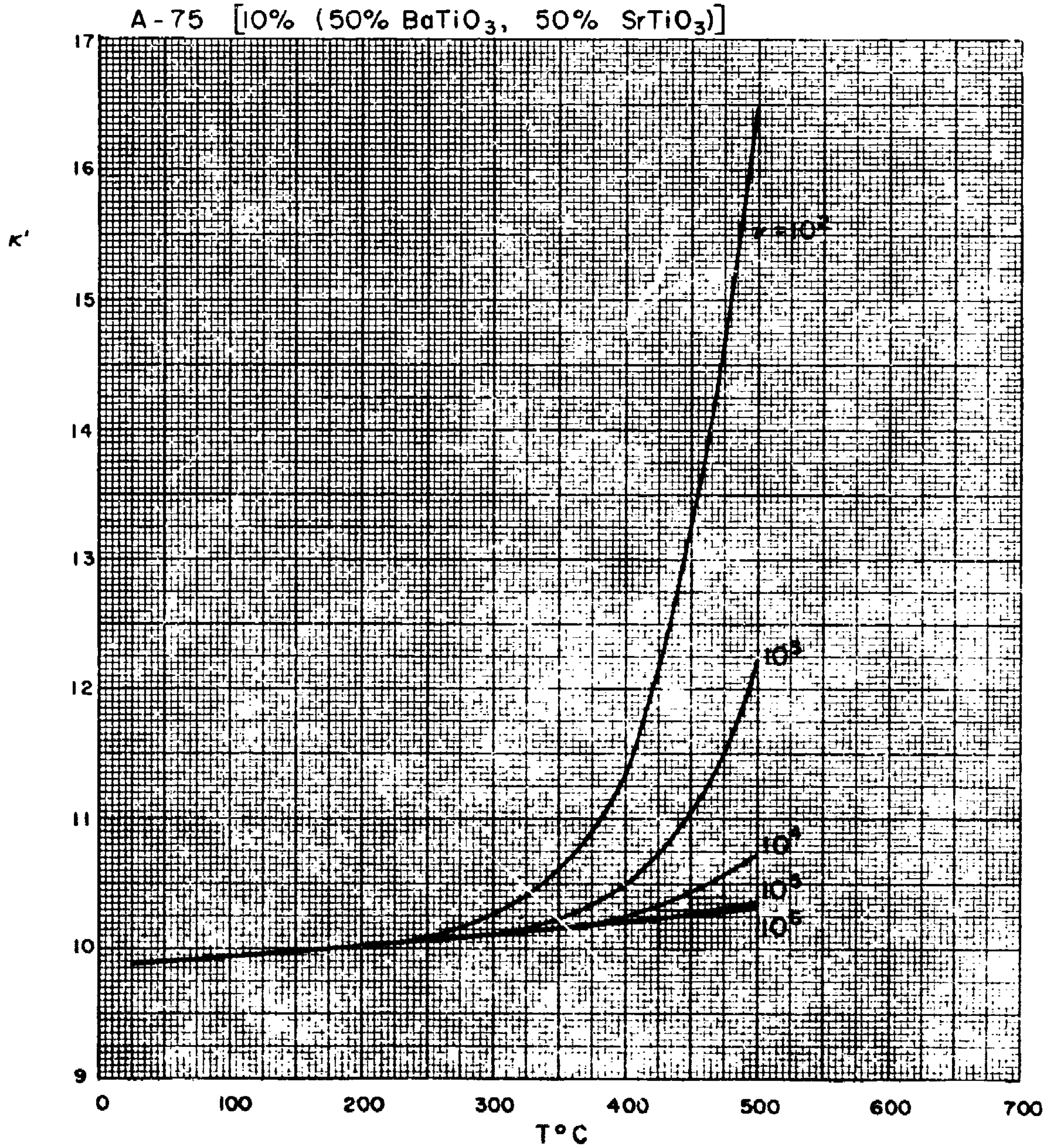
Alumina, hot-pressed   Armour Research Foundation



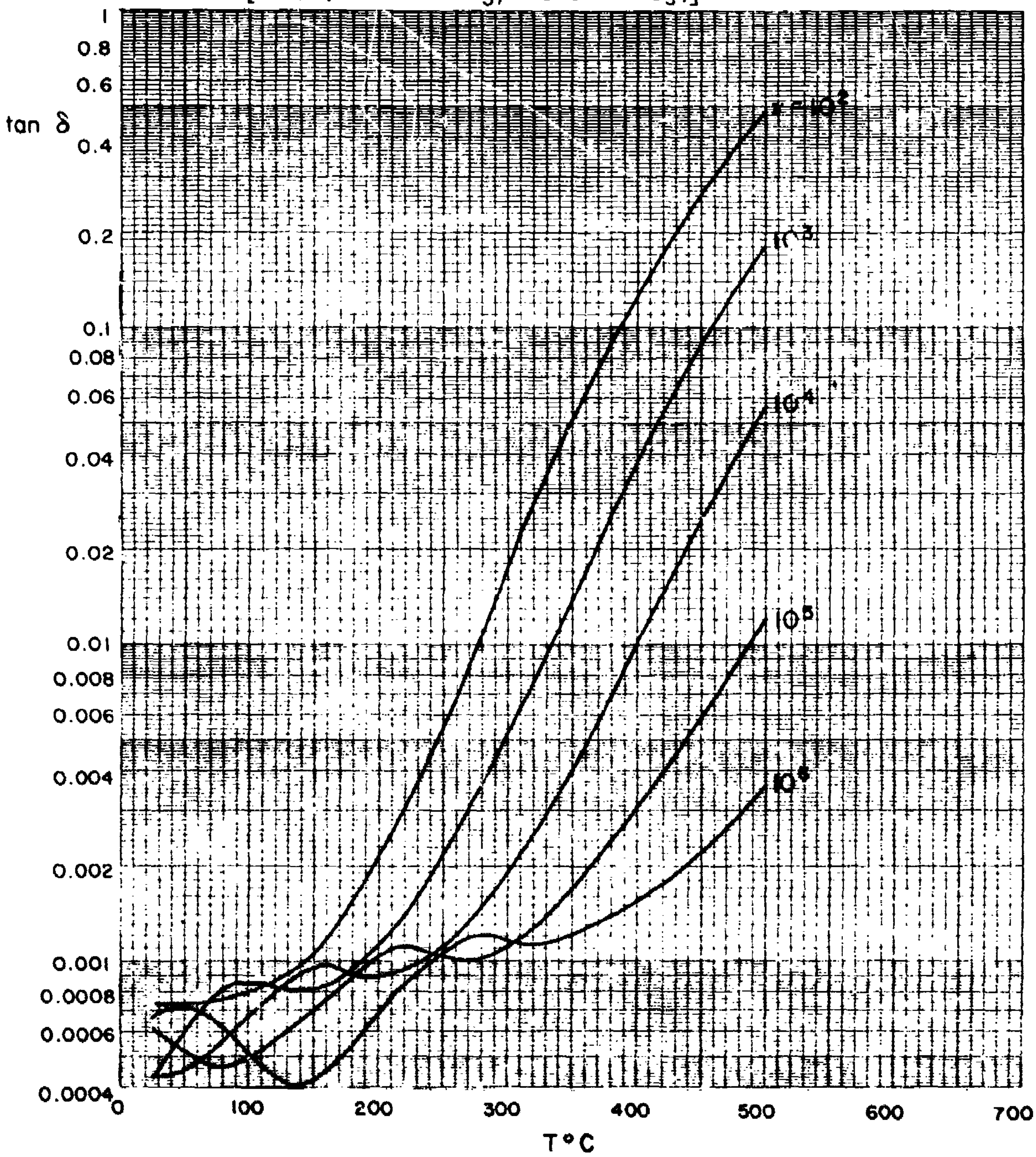


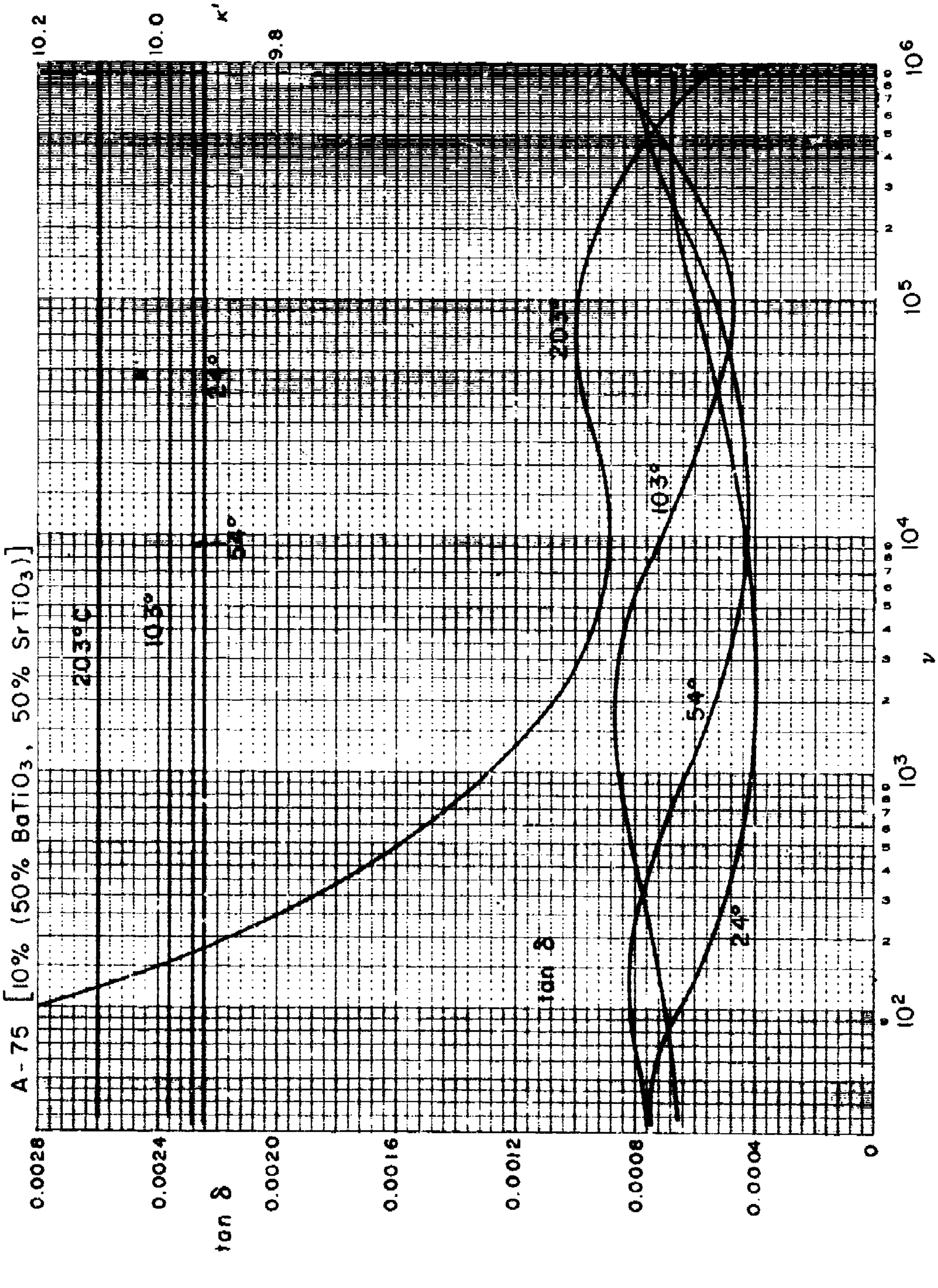
Alumina with 10% titanate addition

Armour Research Foundation

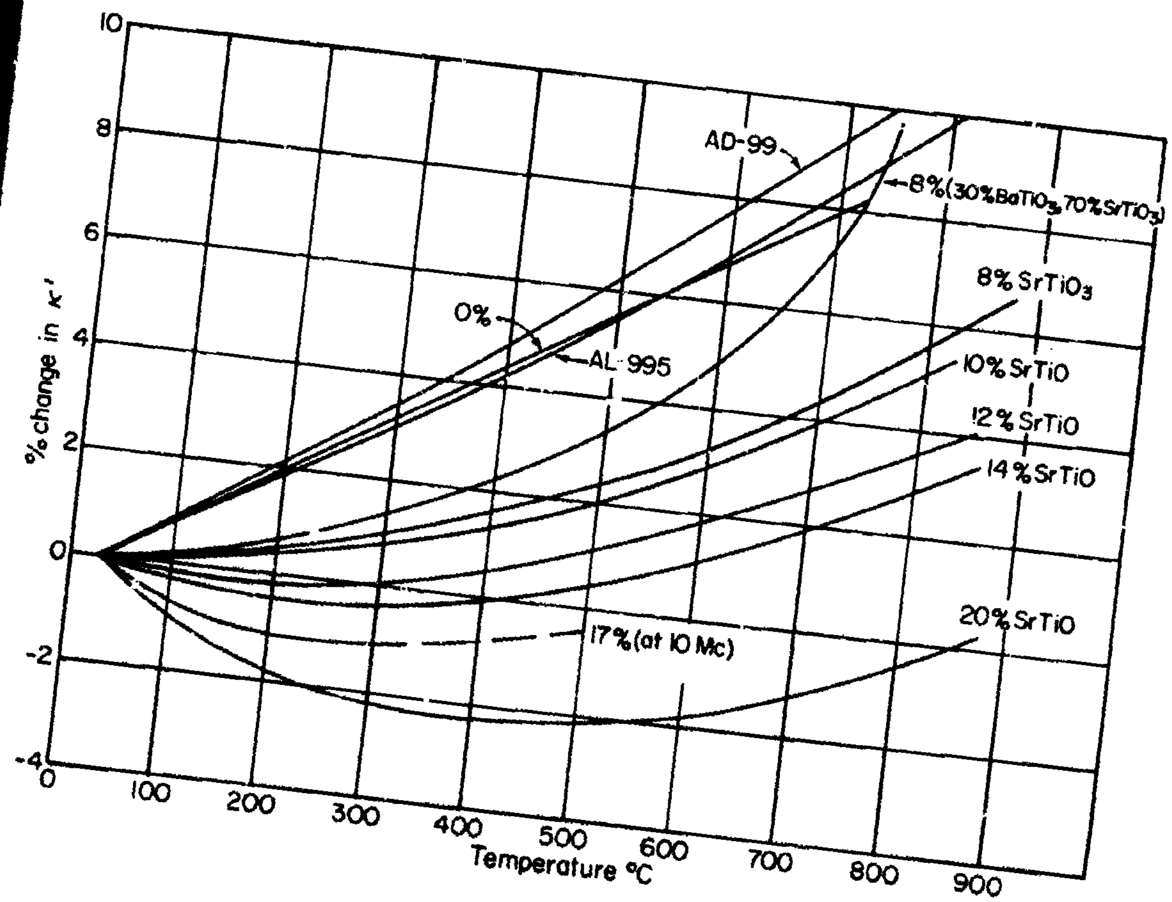


A-75 [10% (50% $BaTiO_3$, 50% $SrTiO_3$)]

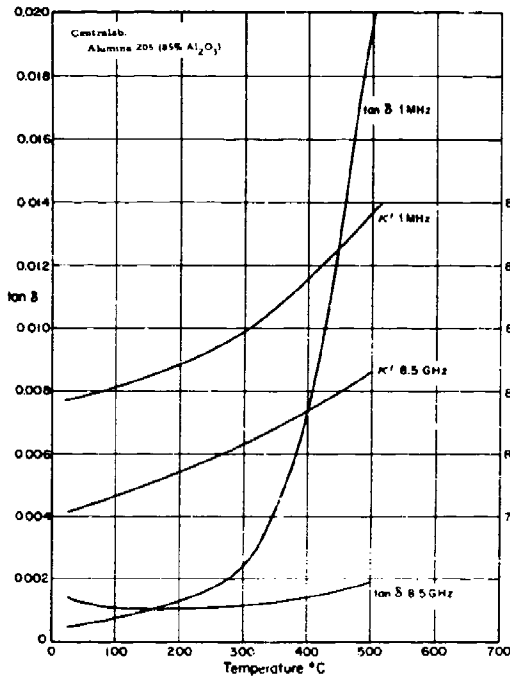


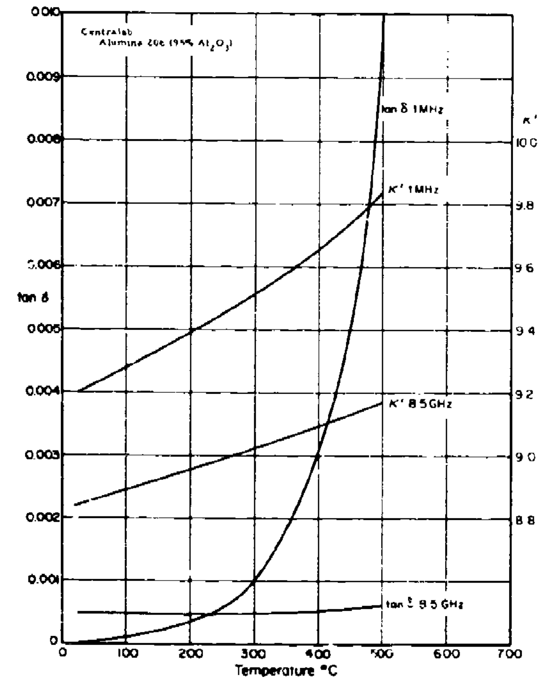

A - 75 [10% (50% BaTiO3, 50% Sr TiO3)]
10.2
10.0
κ'
9.8
203°C
103°
24°
54°
203°
103°
54°
24°
tan δ
0.0028
0.0024
0.0020
0.0016
0.0012
0.0008
0.0004
0
tan δ
10^2
10^3
10^4
10^5
10^6
ν

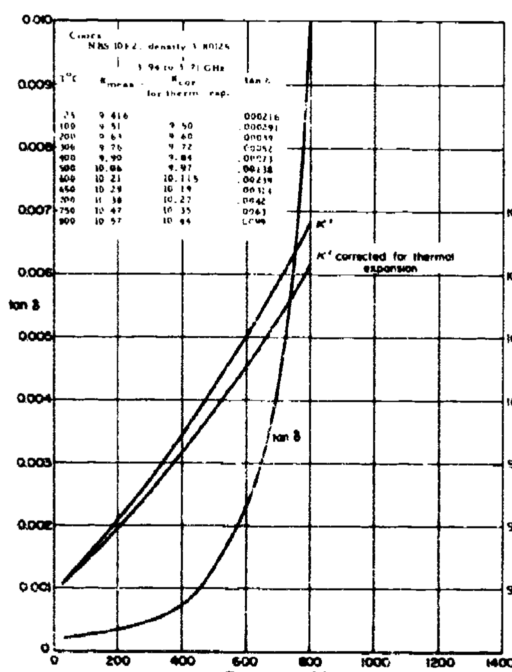
Change in dielectric constant with temperature for various aluminas at ca. 4000 MHz



Alumina (cont.)







Frenchtown 7225

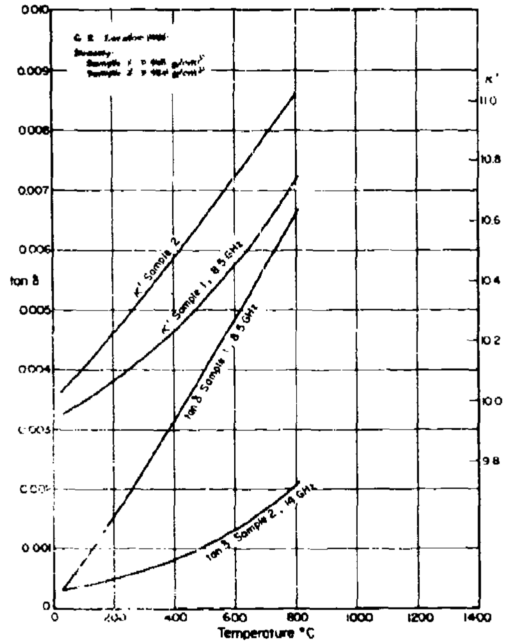
8.52 GHz, 25°C

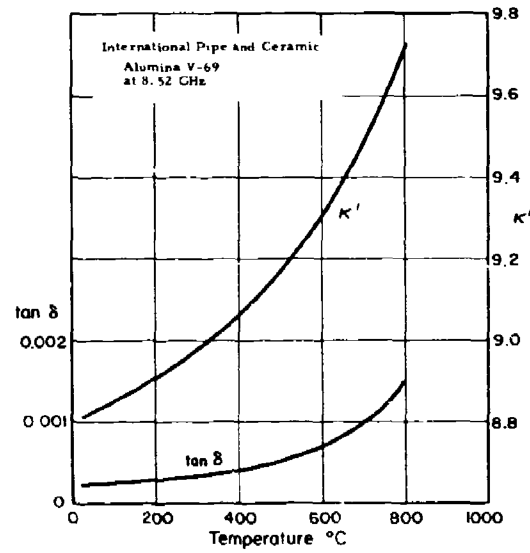
$\kappa' = 8.8 \pm 0.05$

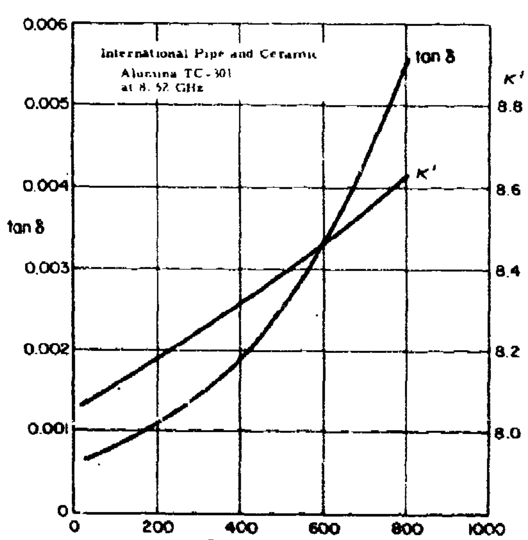
$\tan\delta = 0.0013 \pm 0.0002$

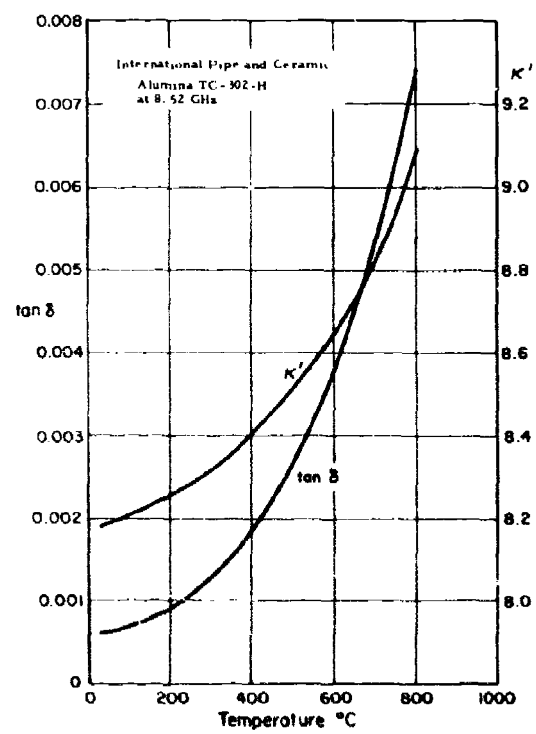
on two samples

Alumina (cont.)



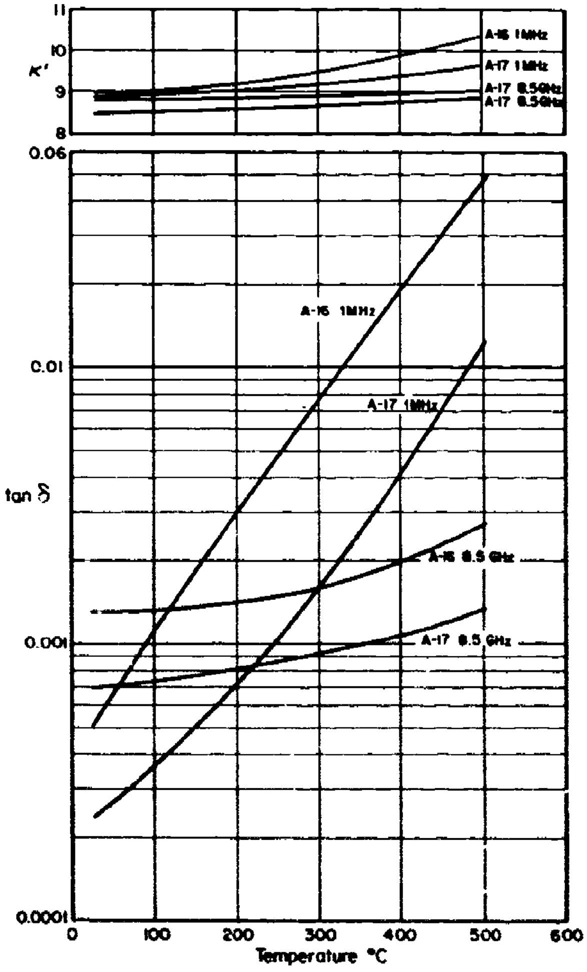






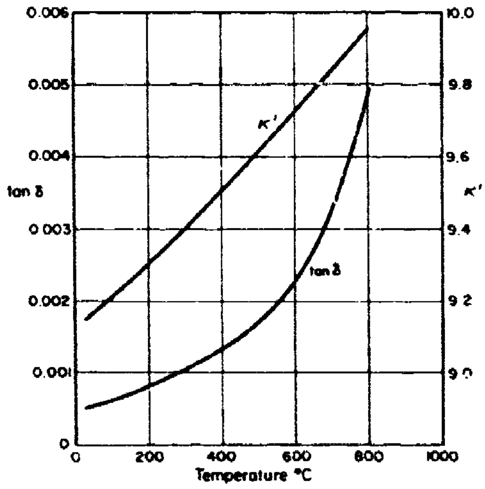
Raytheon

Aluminas 1959



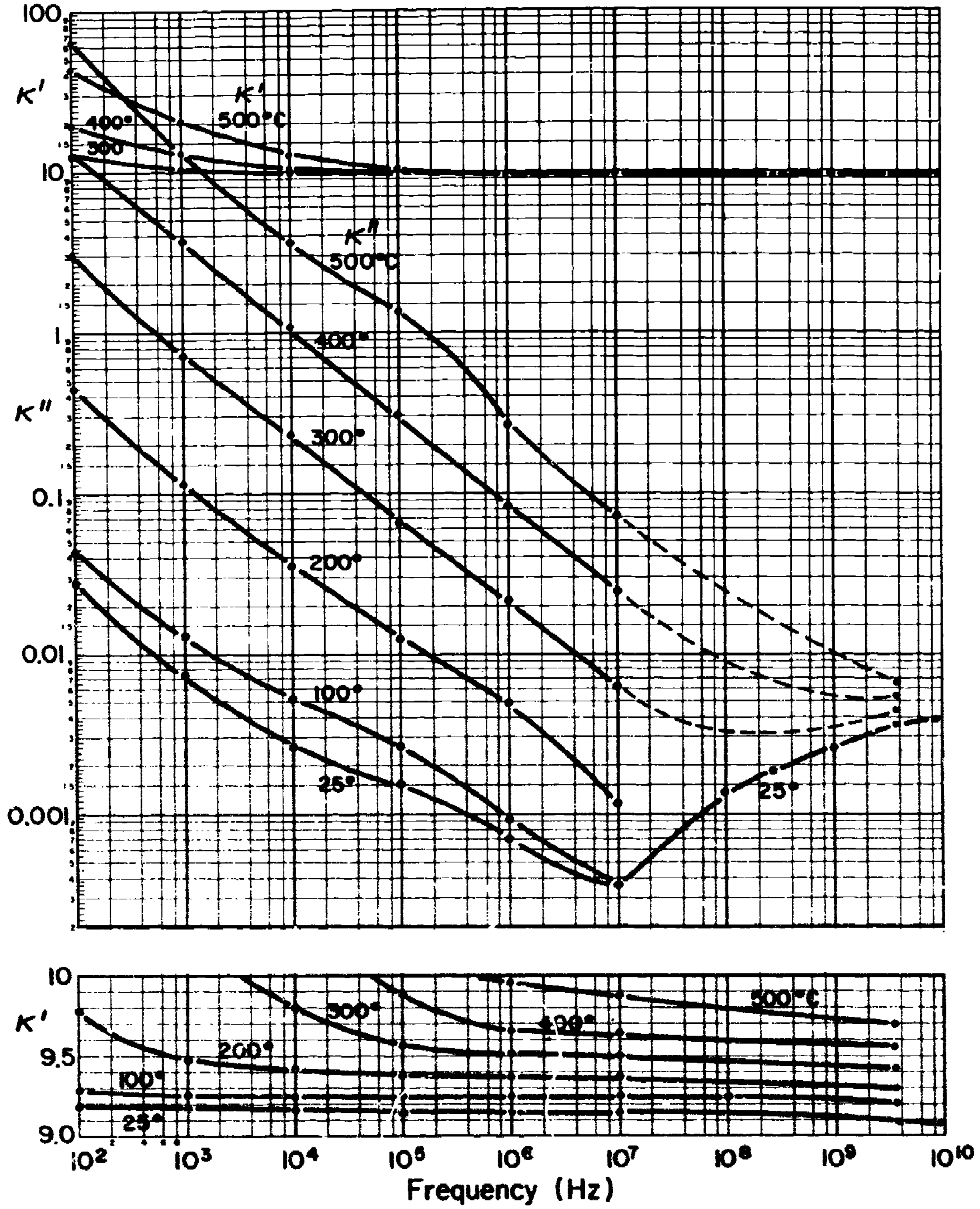
International Pipe and Ceramic

TC-351
at 8.52 GHz



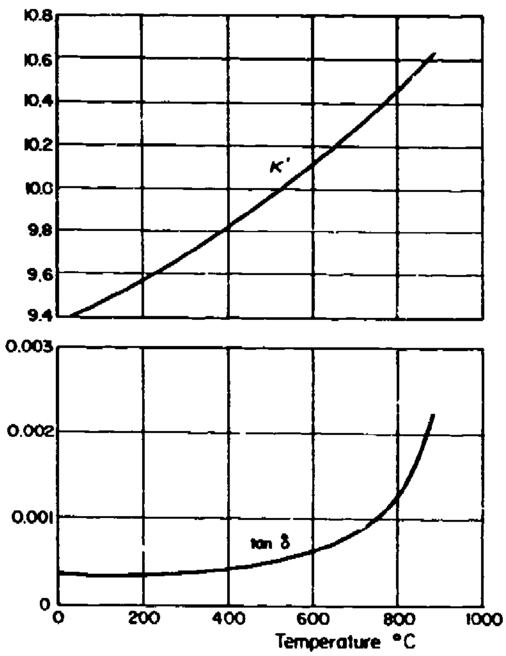
Alumina A-18
Density 3.676 g/cm^3

Steatit-Magnesia Aktiengesellschaft



Alumina, Western Gold and Platinum

Al-300 modified
Density 3.771 g/cm^3
4.1 to 3.85 GHz



T°C	κ'	tan δ
25	9.39	.00037
122	9.48	.00037
185	9.55	.00038
258	9.63	.00038
339	9.74	.00041
393	9.79	.00045
500	9.95	.00055
572	10.08	.00064
788	10.43	.00120
881	10.63	.00219

At 25°C

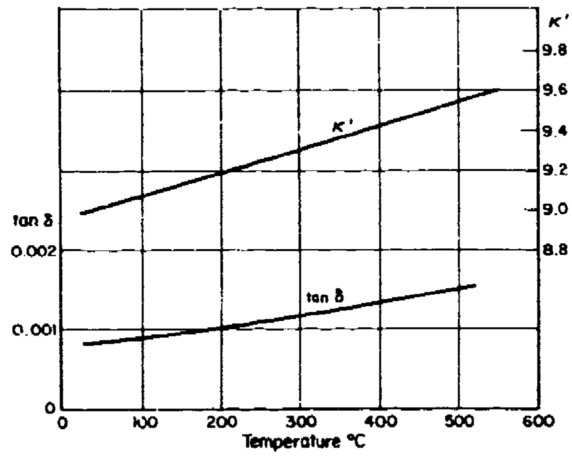
f (Hz)		
10^7	9.44	.00012
10^9	9.40	.00035
3×10^9	9.39	.00037
8.5×10^9	9.38	.00046

Alumina, Western Gold and Platinum

Al-500
Density 3.665 g/cm

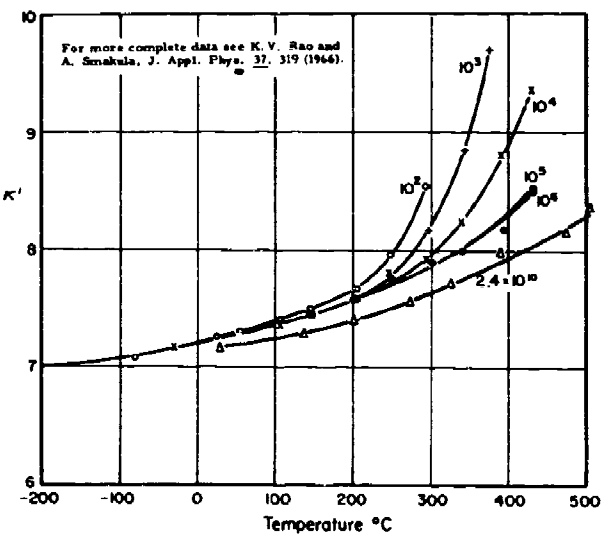
At 25°C

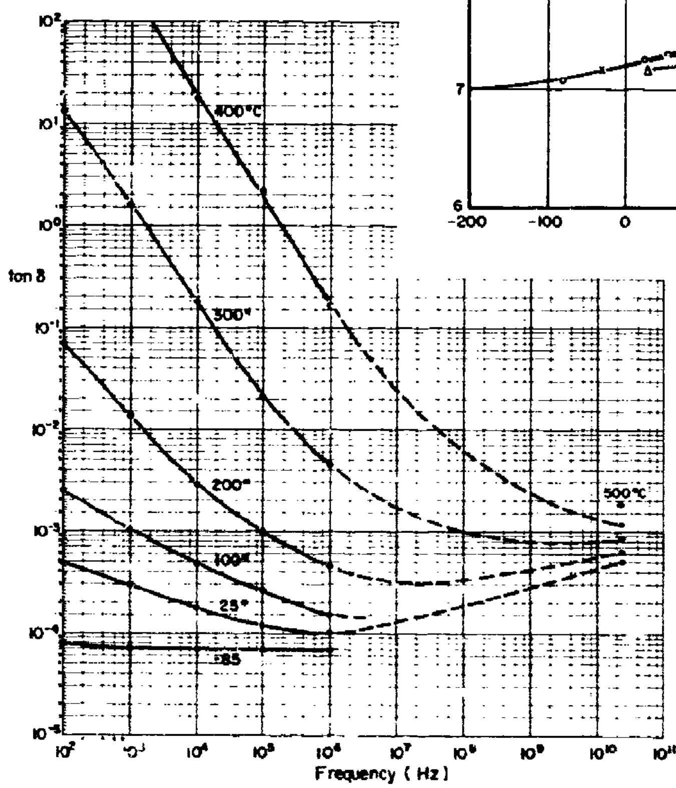
f (Hz)	κ'	tan δ
10^7	9.07	.00026
10^9	9.03	.00062
3×10^9	9.02	.00070
8.5×10^9	see the graph below	



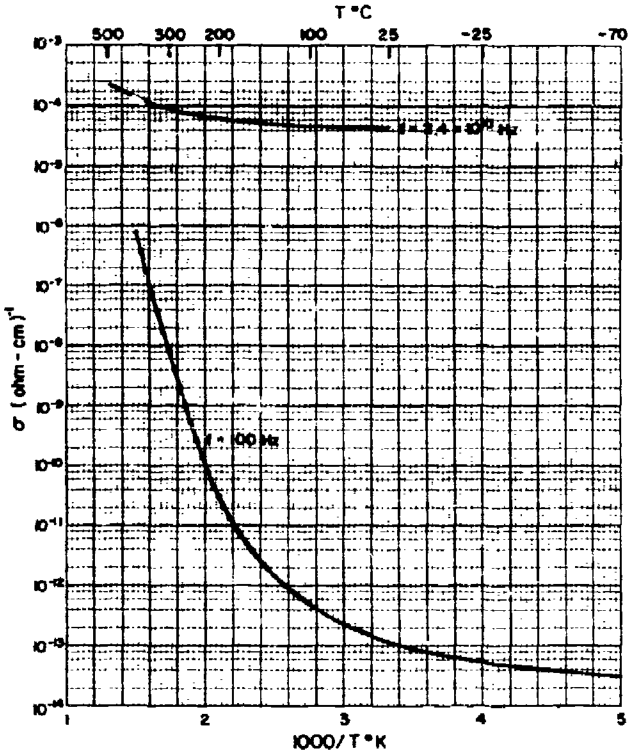
Barium Fluoride

Massachusetts Institute of Technology
Crystal Physics Laboratory





Barium fluoride (cont.)



Beryllium oxide

BeO crystal KSC 7011A

Electronic Space Products Inc.

E ∥ c axis

10^2 to 10^7 Hz

$\kappa' = 7.41 \pm 0.1$

$\tan\delta < 0.0006$

American Lava

AlSiMag 754 (99.5% BeO)

Density 2.851 g/cm^3

8.52 GHz

T°C	κ'	tan δ
25	6.86	.00031
300	6.98	.00055
500	7.13	.00062

Coors Porcelain Co.

Beryllia BD98

8.52 GHz

T°C	κ'	tan δ
25	6.67	.00050
300	6.87	.00072
500	7.13	.00102

National Beryllia Corp.

Berlox

8.52 GHz

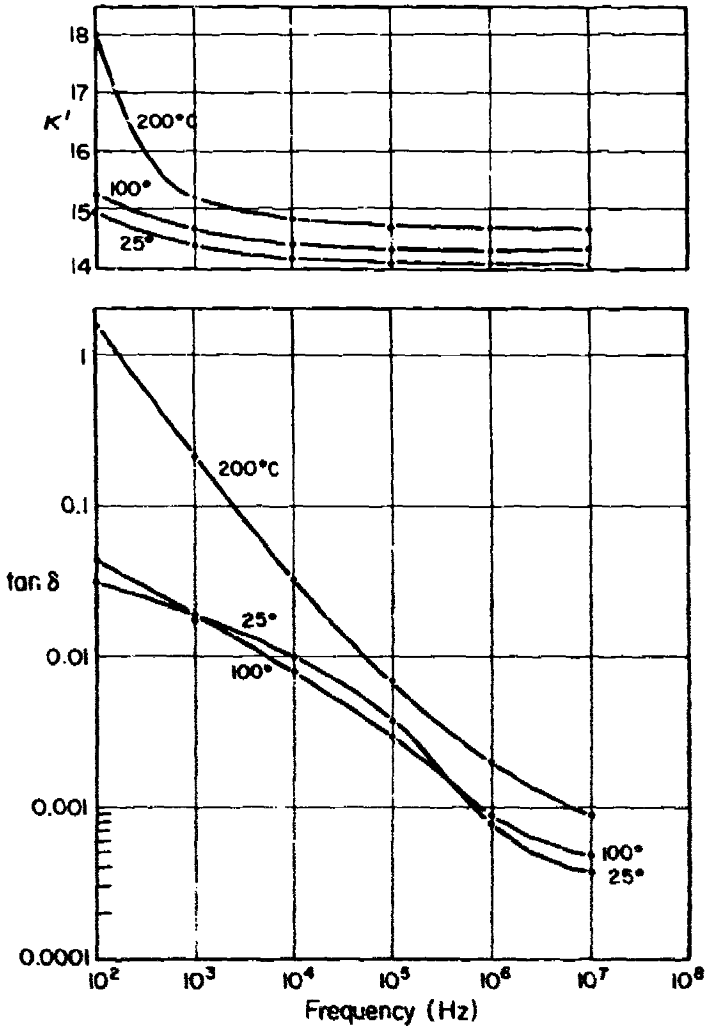
T°C	κ'	tan δ
25	6.64	.00043
300	6.77	.00068
500	6.98	.00093

Beryllium silicate crystal KSC 7013 Electronic Space Products Inc.

E ∥ optic axis

f (Hz)	κ'	tan δ
10^2	$5.1 \pm .5$	.0025
10^5	"	$.0003 \pm 2$

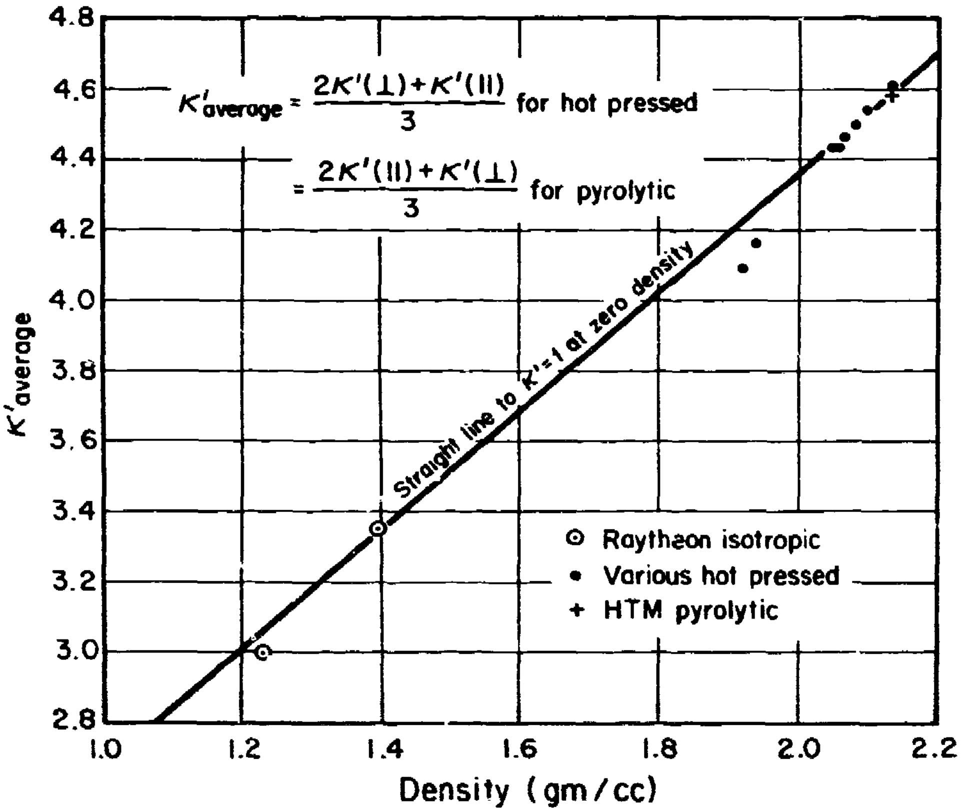
$Bi_4Si_3O_{12}$ ceramic Laboratory for Insulation Research



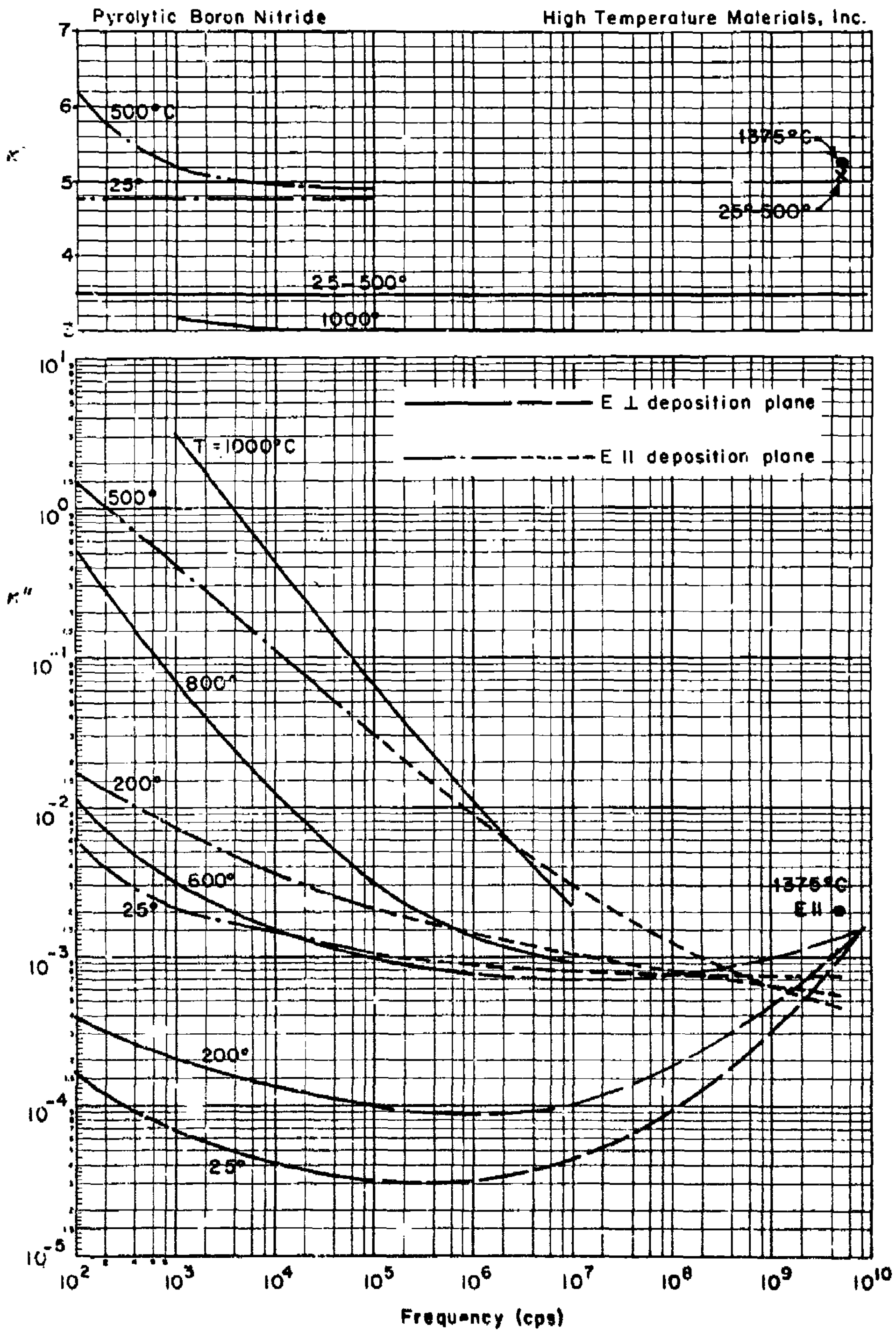
Boron nitride

Average dielectric constant versus density

X-ray density 2.25 g/cm^3



K' $\perp$: electric field $\perp$ direction of unidirectional hot press or electric field $\perp$ deposition plane.

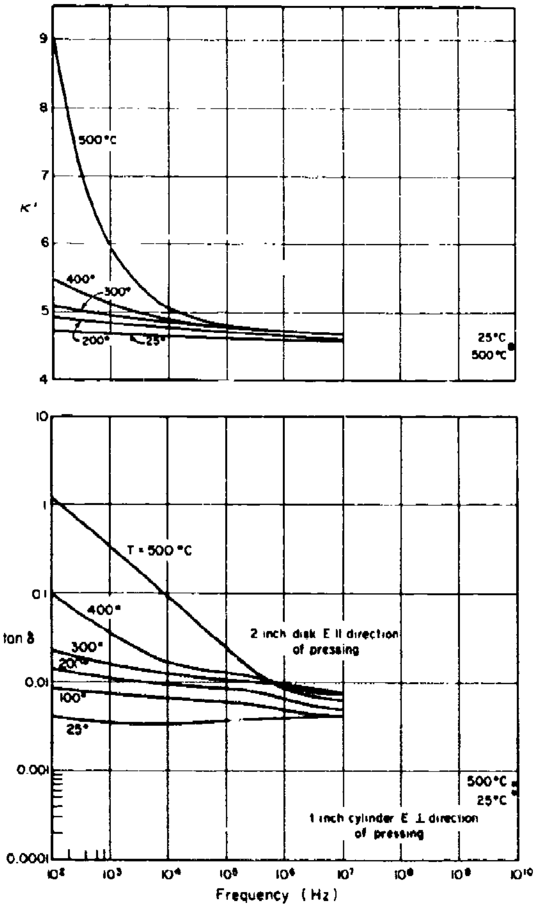


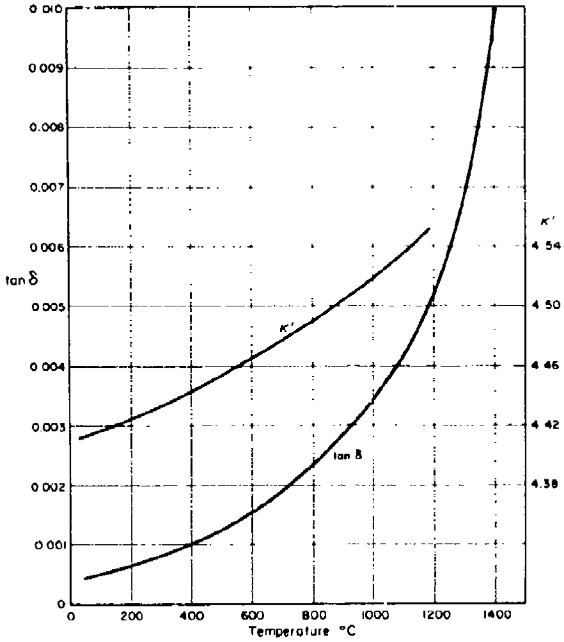
BN, pyrolytically deposited, High-Temperature Materials, Inc., "Boralloy." The microwave data show a small peak possibly due to loss of impurities (perhaps OH ions) at about 800°C. Graphite electrodes and prepurified N_2 used in low-frequency measurements which showed variations among different samples.

Hot-pressed boron nitride, grade HBN

Carbon Products Division
Union Carbide Corp.
(Formerly National Carbon Co.)

4.95 to 4.88 GHz



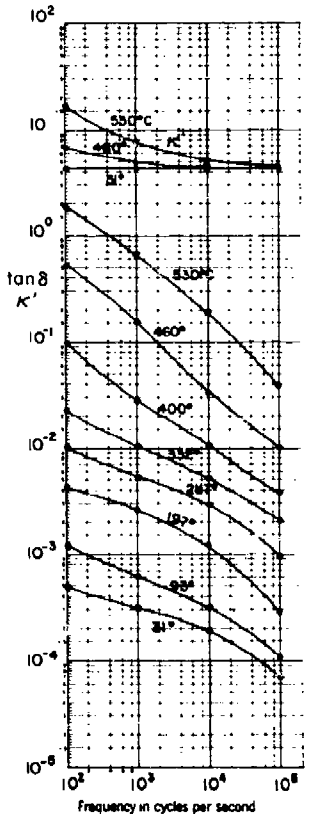


Density 2.054 g/cm^3

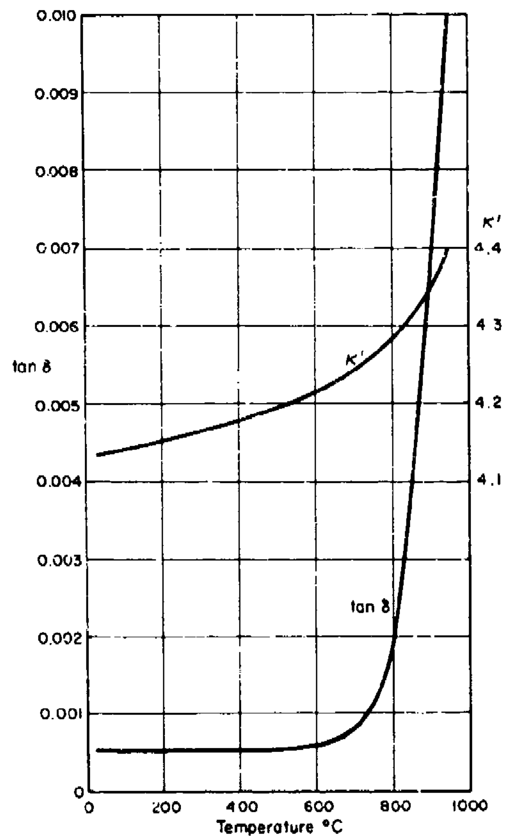
1" cylinder, 8.52 GHz

$T^{\circ}C$	E	κ'	tan δ
25	⊥	4.38	.00050
25	‖	4.52	.00056
100	‖	4.52	.00056
200	‖	4.51	.00061
300	‖	4.50	.00064
400	‖	4.49	.00066
500	‖	4.48	.00073

Hot-pressed boron nitride
Grade HD0056



Grade HD 0086
Density 1.940 g/cm^3
5.17 to 4.96 GHz



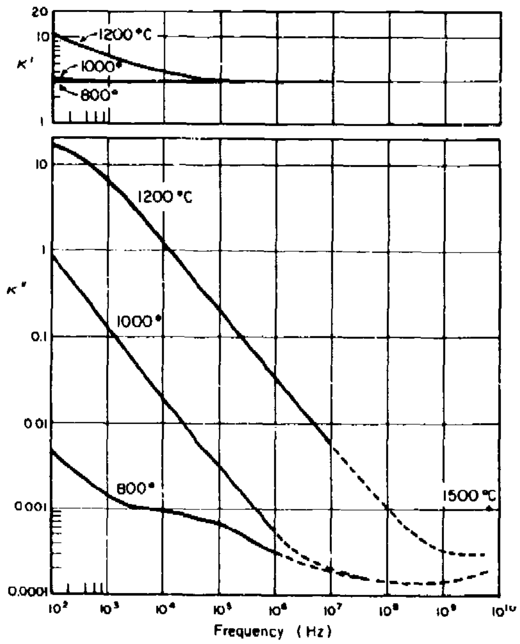
8.52 GHz

T°C	E	κ'	tan δ
25	∥	4.31	.00053
25	⊥	4.10	.00055
100	⊥	4.08	.00059
200	⊥	4.07	.00066
300	⊥	4.06	.00075
400	⊥	4.05	.00086
500	⊥	4.05	.00102

Pyrolytic boron nitride

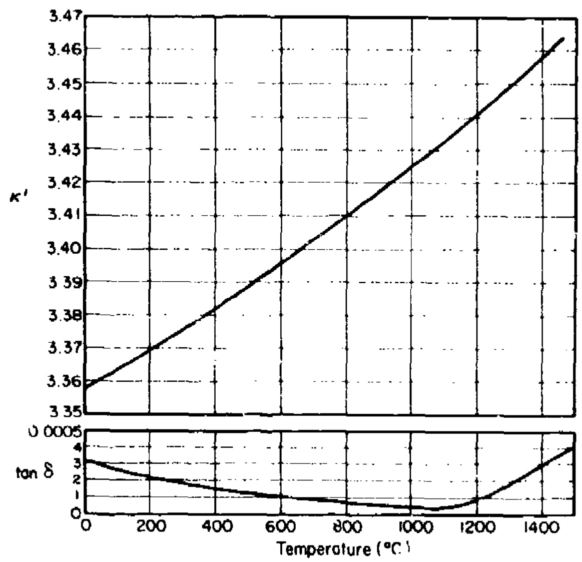
Raytheon

Density 1.23 g/cm^3



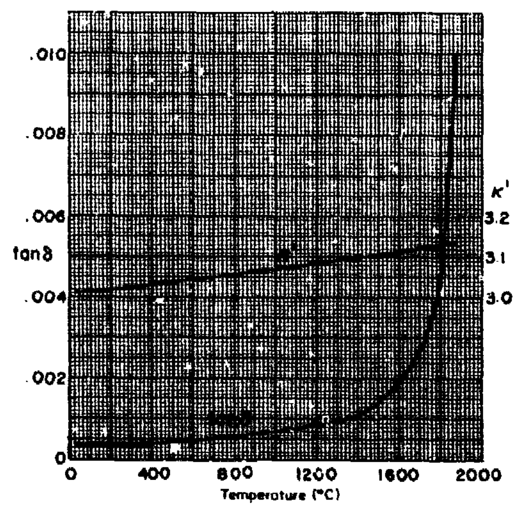
At 5.74 to 5.65 GHz

Density 1.398 g/cm^3



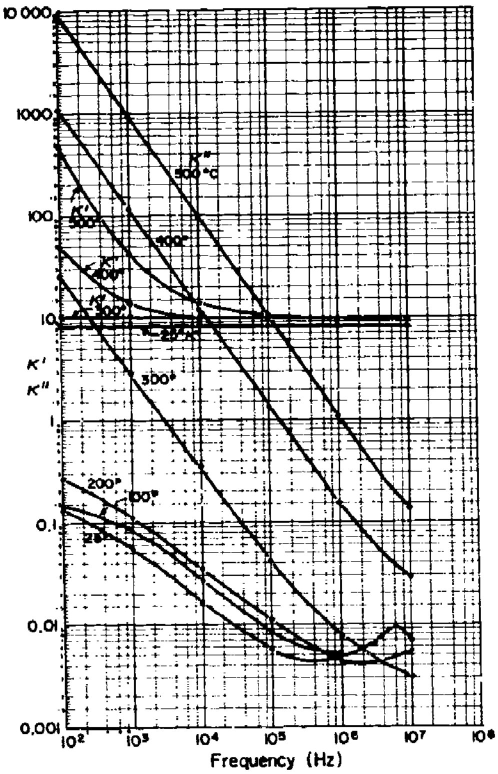
Density 1.23 g/cm^3

At 9.21 to 9.04 GHz

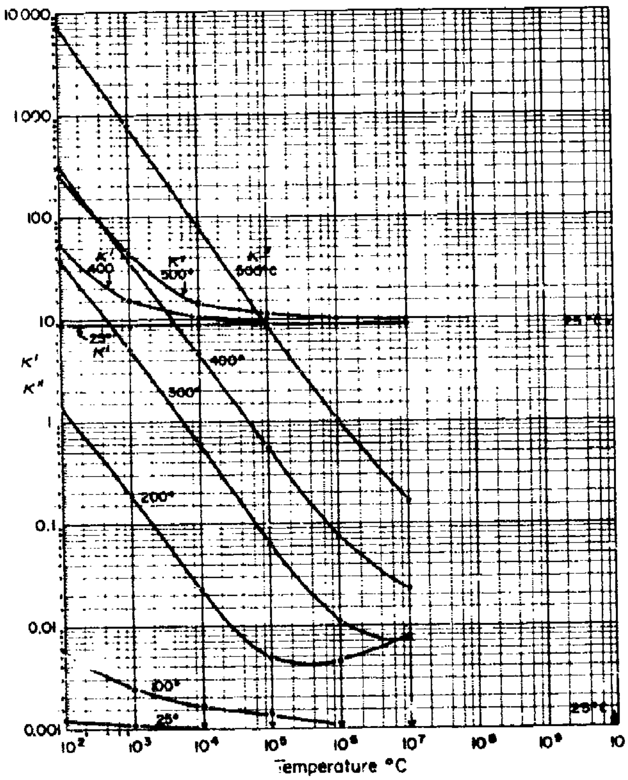


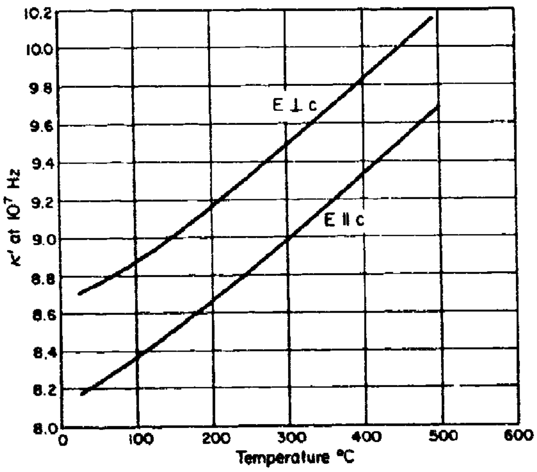
Calcium carbonate
Calcite, single crystal mineral

E ∥ c, crystal No. 1



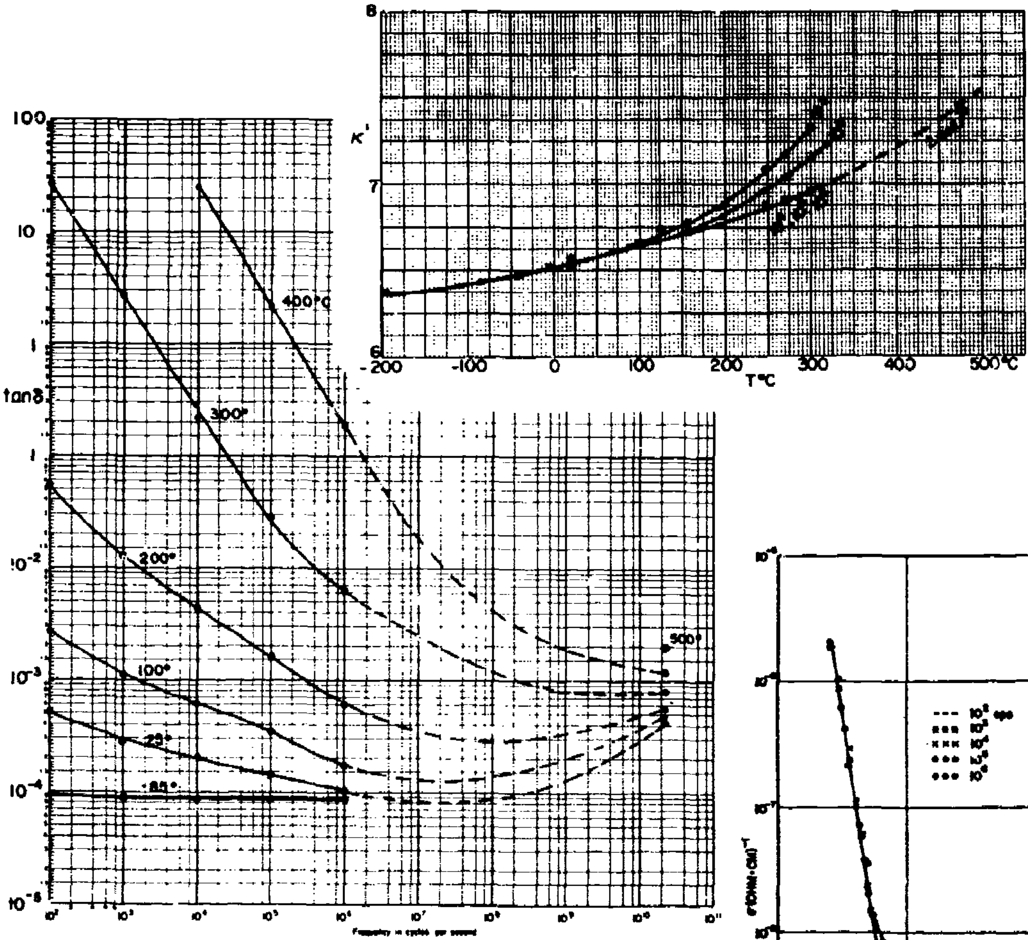
E ⊥ c, crystal No. 2

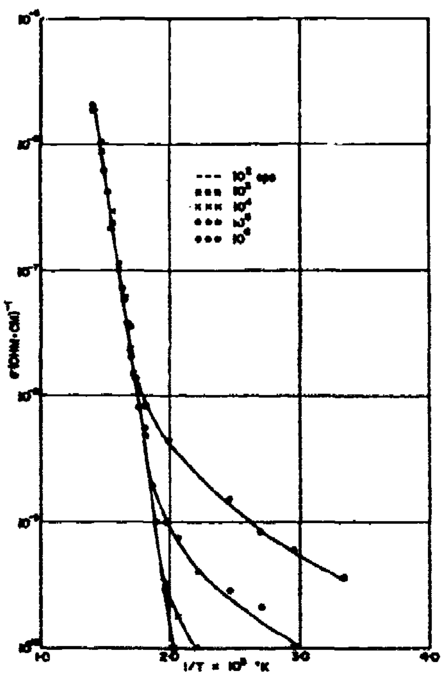




Calcium fluoride crystal

M.I.T., Crystal Physics Laboratory

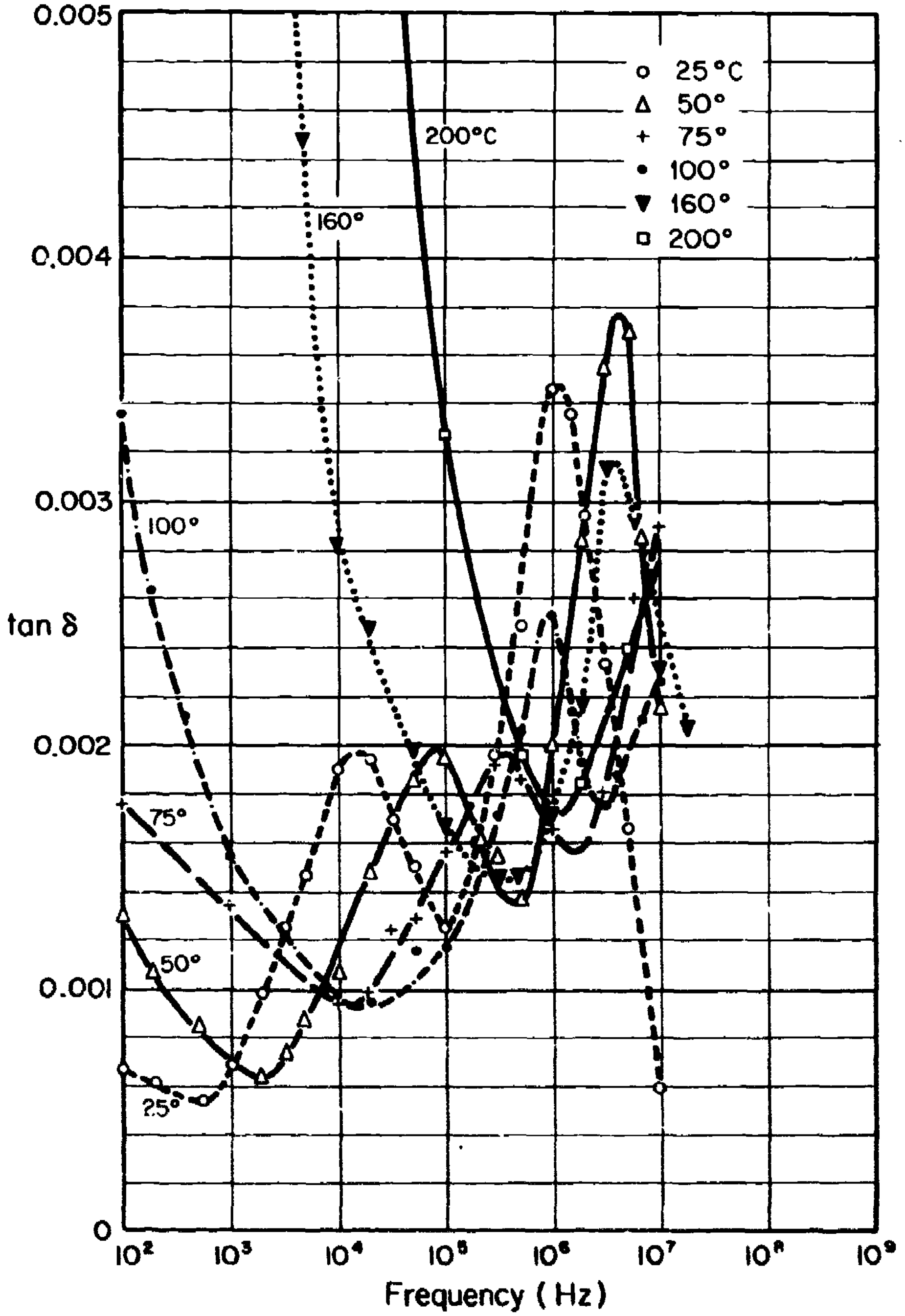




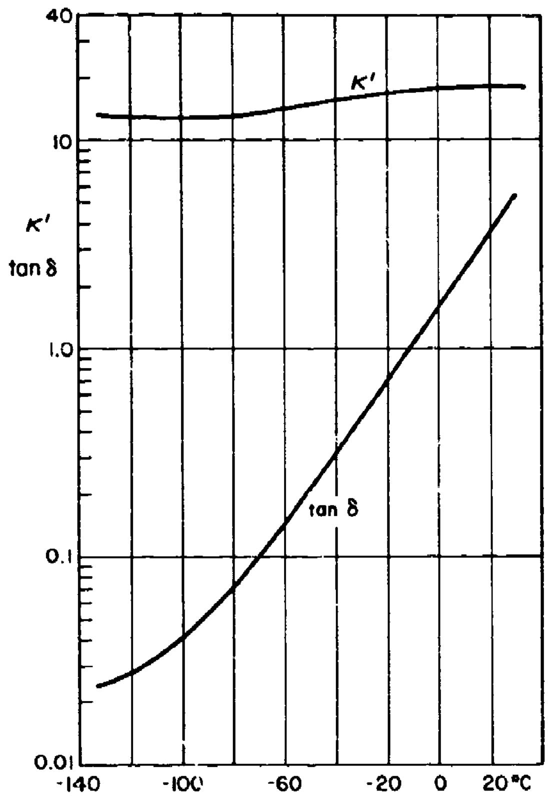
For more complete data see K. V. Rao and A. Smakula, J. Appl. Phys. 37, 319 (1966).

Calcium fluoride doped with Y_2O_3

M. I. T., Department of Metallurgy, Ceramics Lab.



Cerium fluoride, at 1 MHz — M. I. T., Lab. Ins. Res.



Cobalt oxide — M. I. T., Crystal Physics Lab.

Cobalt oxide-nickel oxide

At 25°C, 1 MHz

	κ'	tan δ
CoO	12.9	.0005
CoO·NiO 50/50 mole percent	40	.39

For complete data see:
K. V. Rao and A. Smakula, J. Appl. Phys. 36, 2031 (1965).

Copper halide pressed powders — M. I. T., Lab. Ins. Res.

Measured values at 14 GHz

	Sample density / X-ray density	κ'	tan δ
CuBr	4.85/5.17	6.33	< .001
CuCl	3.68/4.10	6.52	< .001
CuI		27.8	.112

Lead halides

M. I. T. Crystal Physics Laboratory

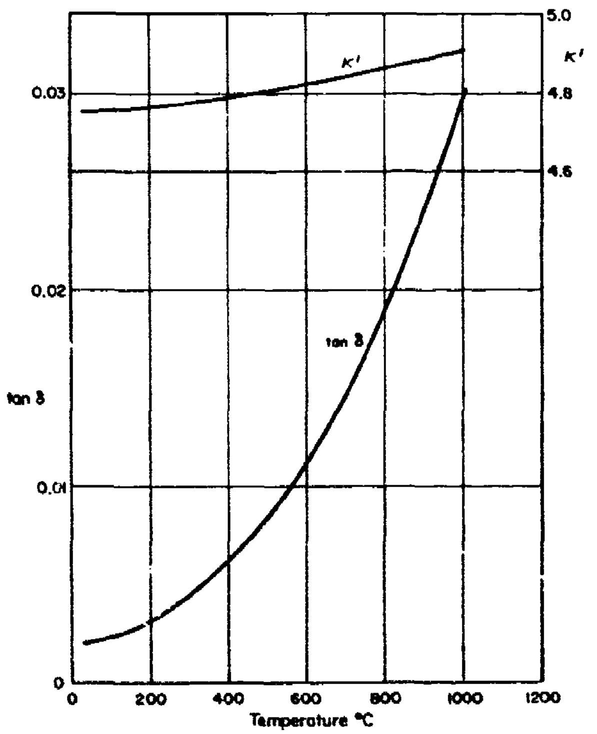
	Electric field dir. parallel to		At 1 MHz, 25°C κ'	tan δ	Activation energy for "intrinsic" conduction
$PbBr_2$	a	4.72	52.7	.0052	-
	b	8.06	56.3	.0033	-
	c	9.55	25.3	.0033	-
$PbCl_2$	a	4.53	47.4	.11	.30 eV
	b	7.62	51.3	.065	.28 eV
	c	9.05	24.8	.051	.42 eV
$PbCl_2$-$PbBr_2$ 85/15 mol %	c		28.5	.016	1.1 eV

For additional data on these materials see: A. Smakula, Tech. Rep. No. 6, (Final Report under Contract Nonr 1841(88)), M. I. T., Crystal Phys. Lab., March 11, 1965.

Magnesium aluminum silicate

Cordierite ceramic, Raytheon Co.

8.52 GHz



Magnesium carbonate, hard-packed fine powder, reagent grade, at 8.52 GHz, 25°C:

κ'	tan δ
1.282	.0109

Density .189 g/cm^3

Transparent MgO ceramic
IRTRAN-5

Kodak

Density = 3.57 g/cm^3, 25°C

f (Hz)	κ'	tan δ
10^2	9.82	.0014
8.5×10^9	9.72	.00045

Magnesium metasilicate,
multicrystalline, F-66

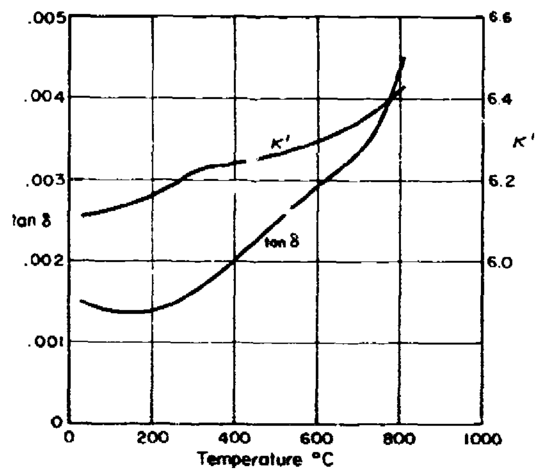
Bell Telephone Laboratories

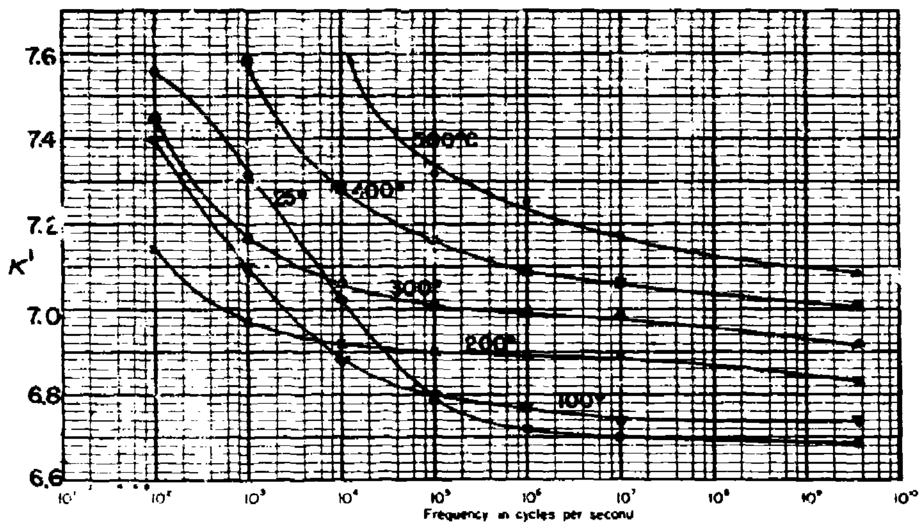
14 GHz

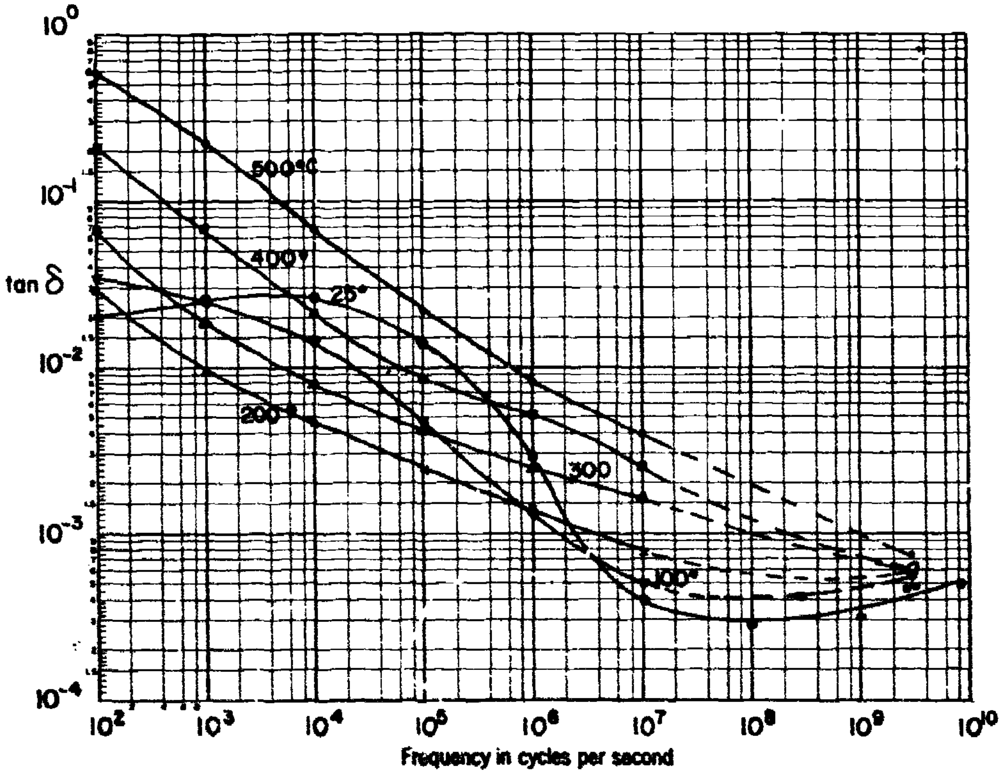
T$^\circ$C	κ'	tan δ
25	6.37	.0012
100	6.39	.0012
200	6.43	.0012
300	6.47	.0012
400	6.52	.0013
500	6.58	.0015
600	6.67	.0020
700	6.75	.0047
800	6.85	.0165

International Pipe and Ceramic Corp.
(Gladding McBean and Co.)

Steatite TC-503, 8.52 GHz

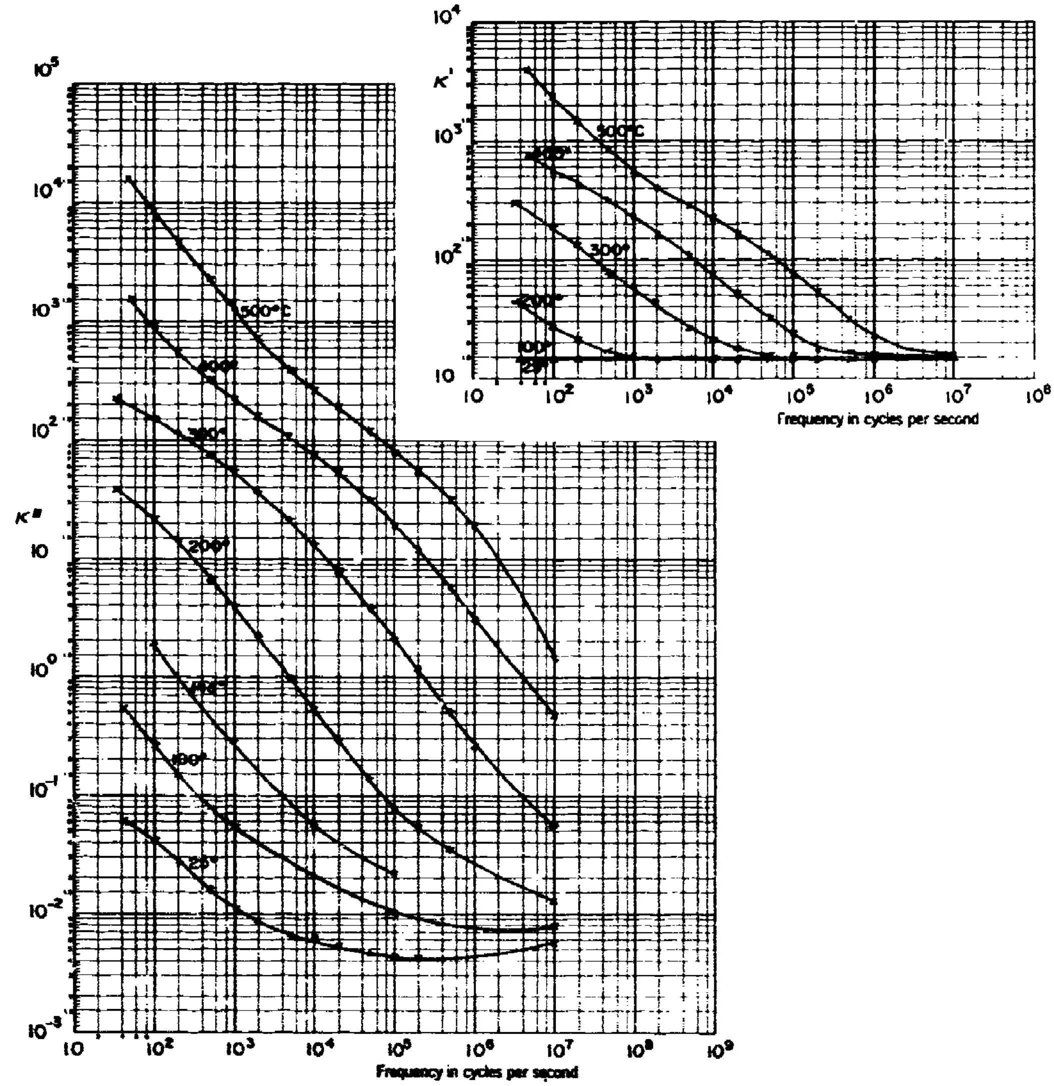



7.6
7.4
7.2
7.0
6.8
6.6
κ'
500°C
400°
25°
300°
200°
100°
Frequency in cycles per second


10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
tan δ
500°C
400°
25°
200°
300
100°
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10}
Frequency in cycles per second

Magnesium titanate ($MgTiO_3$)
Density 3.21 g/cm^3

U. S. Sonics



Manganese fluoride crystal (MnF_2) — Columbia University

f (Hz)	κ'	tan δ	
10^3	$7.2 \pm .2$	.043	E ⊥ to platelike, unoriented crystal
10^7	$6.7 \pm .2$	<.004	

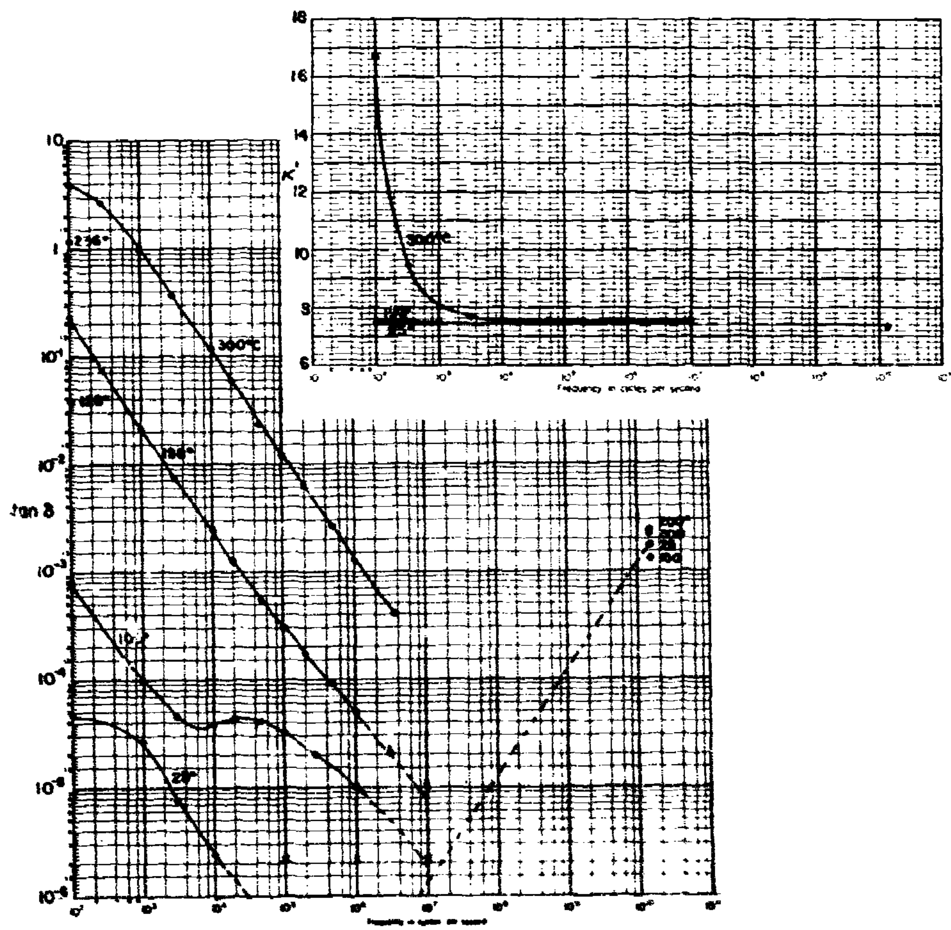
Nickel oxide, NiO, single crystal — M. I. T., Crystal Physics Lab.

At 25°C, 1 MHz

$\kappa' = 11.9$
tan δ = .0154

For complete data see: K. V. Rao and A. Smakula, J. Appl. Phys. 36, 2031-2038 (1965).

Rubidium manganese fluoride — M. I. T., Crystal Physics Lab.



Silicon crystal, intrinsic — M. I. T., Crystal Physics Lab.

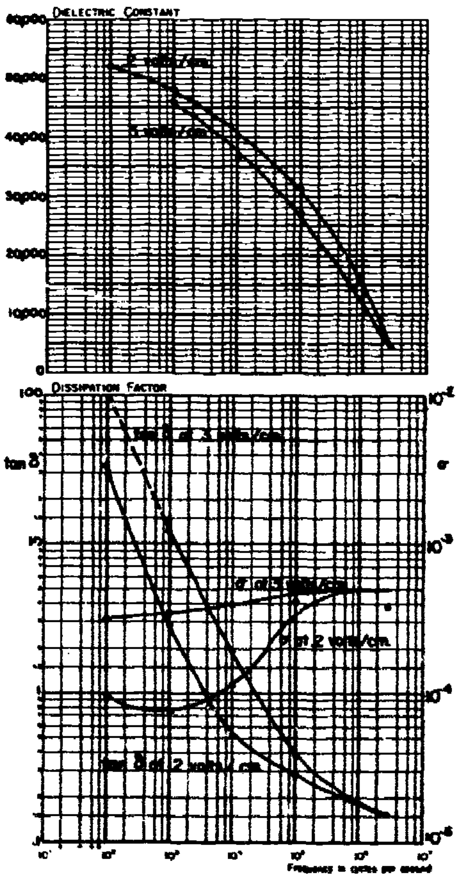
at 25°C

f (Hz)	κ'	tan δ	ρ (ohm-cm)
10^3	-	-	4100
1.4×10^{10}	12.0	.0090	1190

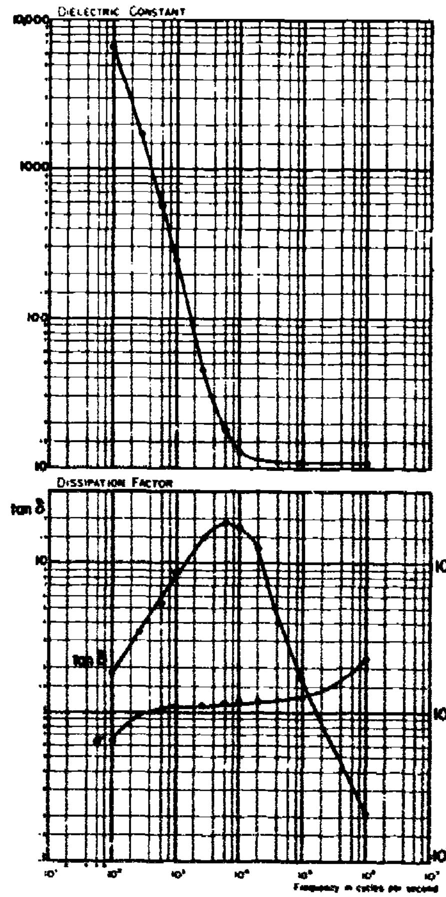
Silicon crystal, undoped — Brown University

Apparent properties of 1 cm cube sample
with evaporated gold electrodes

Silicon single crystal



Radiation damaged single crystal



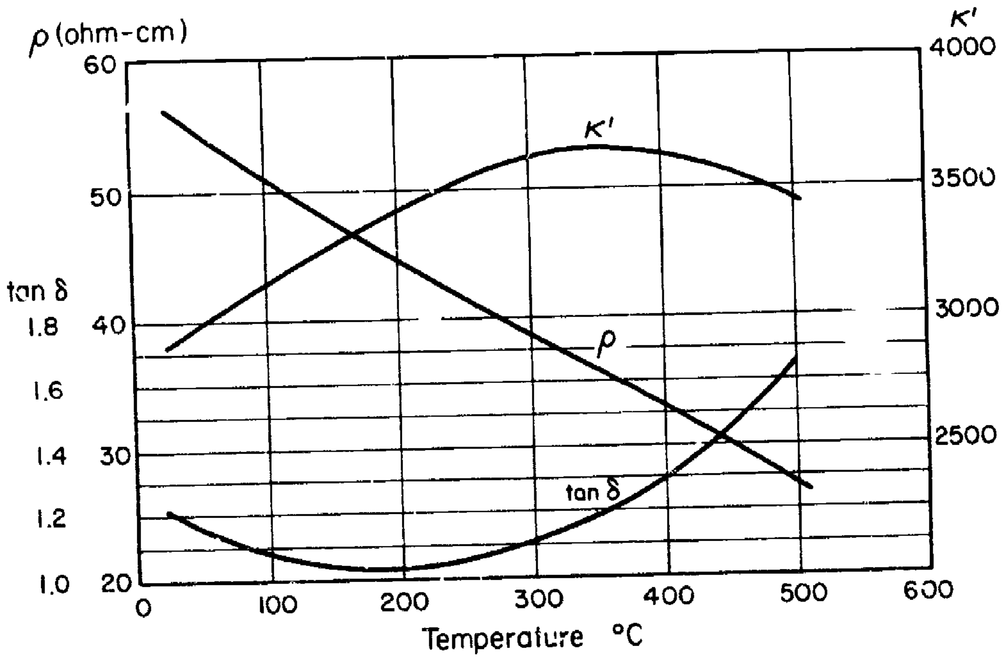
Silicon carbide type attenuator materials — Carborundum

Nominal resistivity (ohm-cm)	Temperature (^{o}C)	f (Hz)	κ'	tan δ	Measured resistivity (ohm-cm)
35	25	3×10^8	167	0.96	37.2
	25	10^9	107	0.686	24.4
	25	3×10^9	60	0.58	17.2
	25	8.5×10^9	47 7	0.55	8.05
0.1	25	8.5×10^9	2130	1.85	0.069
50	25*	10^6	10,150	1.17	151
	25**	10^6	29,450	1.36	45
	25*	10^7	2810	1.21	56.5

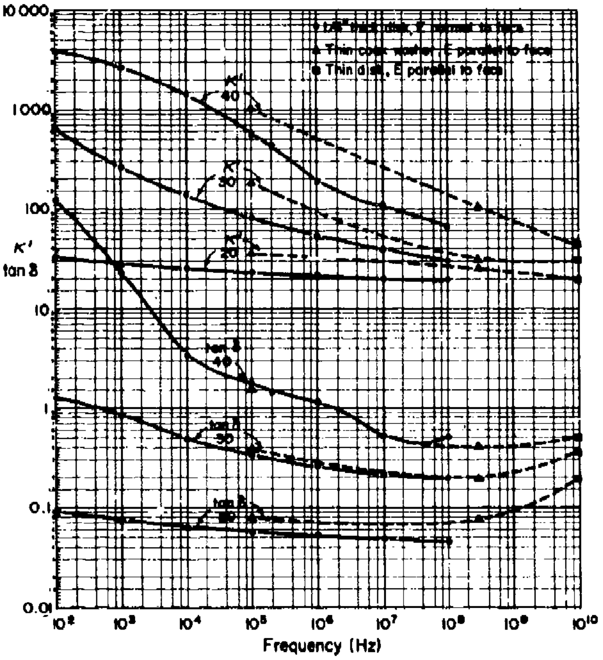
* Two-terminal measurement.

** Four-terminal measurement, different sample

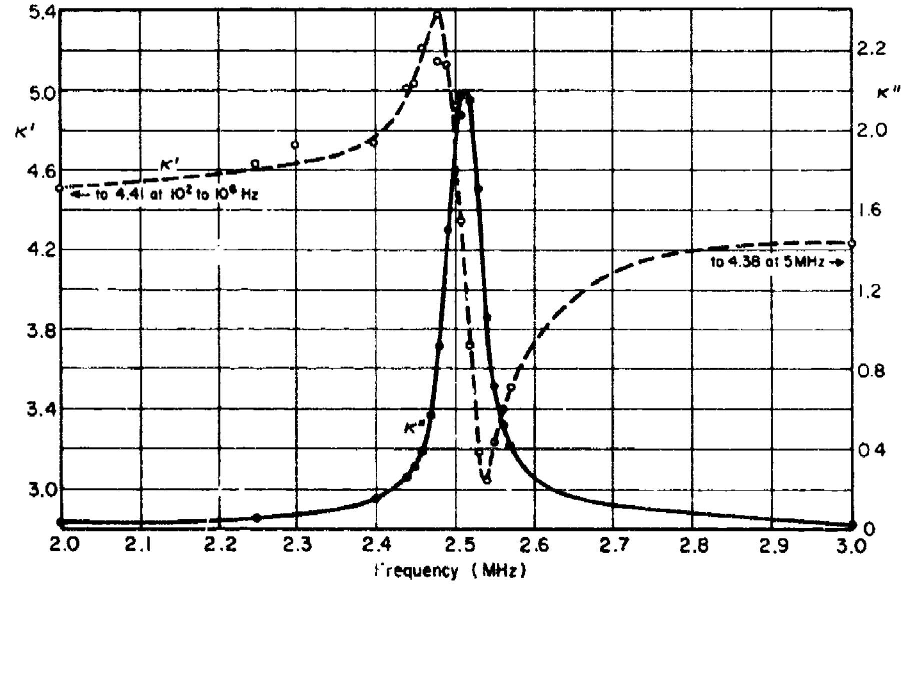
Nominal 50-ohm material at 10^7 Hz



Carberlox 20, 30, 40 National Beryllia Corp.
BeO and silicon carbide ceramic



Silicon dioxide, natural quartz crystal, Fort Monmouth
Y-cut plate, silver paint electrodes, at 25°C



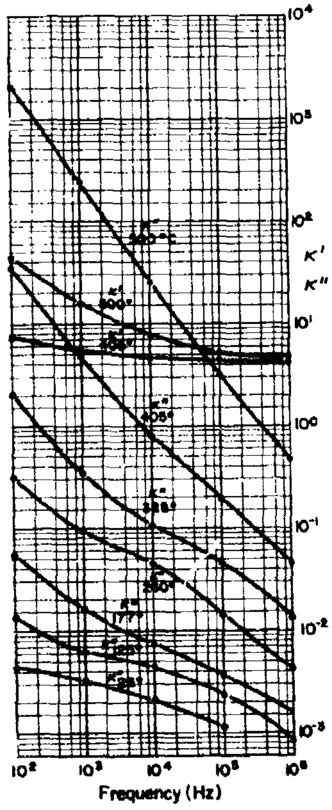
Quartz, continued

Y-cut plate

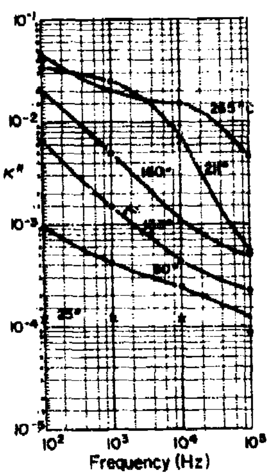
At $25^{o}C$, $\kappa' = 4.40$

$1/\kappa'\left(\frac{d\kappa'}{dt}\right) = -2.8 \times 10^{-5}/^{o}C$

Pt electrodes



Silver electrodes

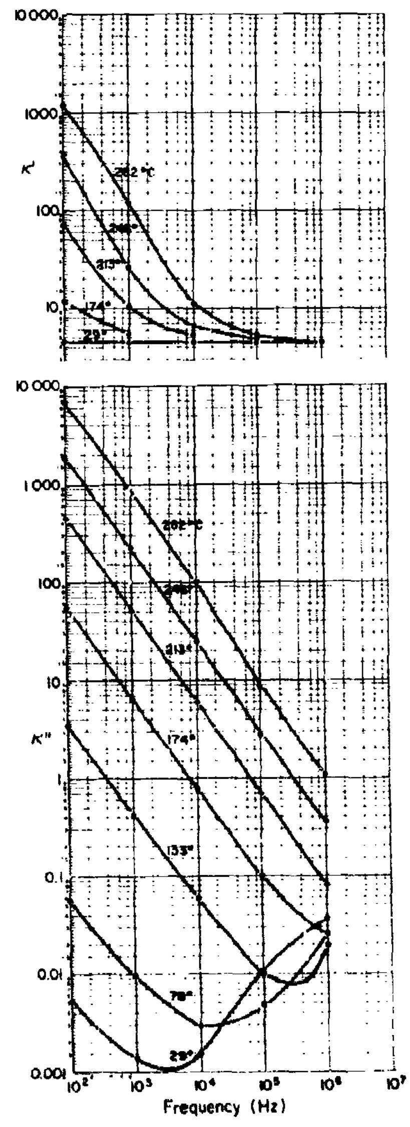


Z-cut plate, E ‖ optic axis

At $25^{o}C$, $\kappa' = 4.64$

$1/\kappa'\left(\frac{d\kappa'}{dt}\right) = -3.9 \times 10^{-5}/^{o}C$

Silver electrodes

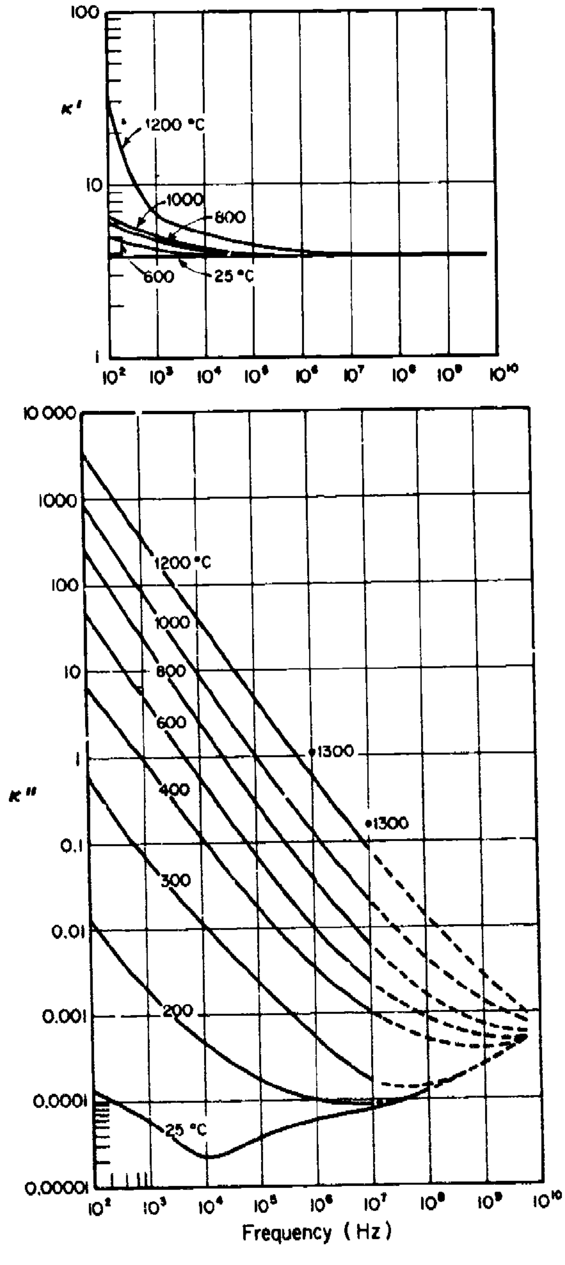


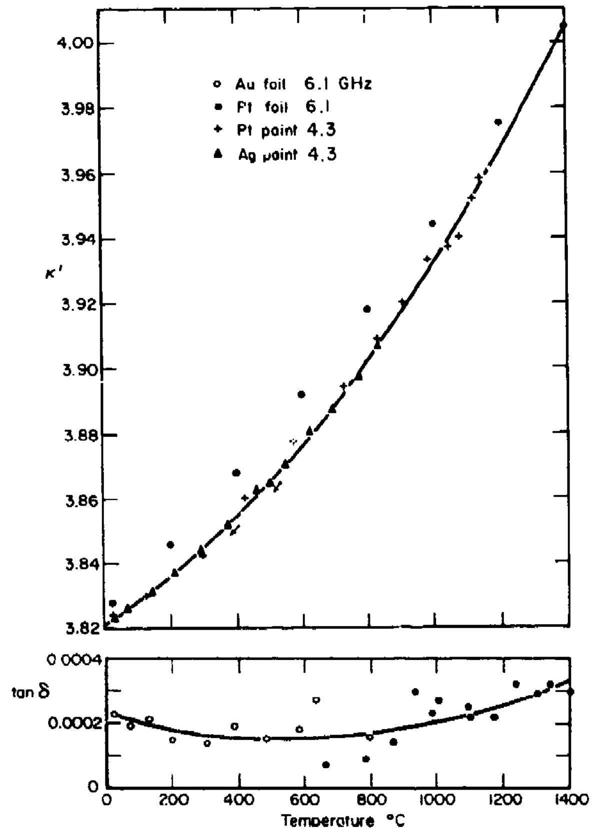
Silicate glasses

Fused silica, Corning 7940

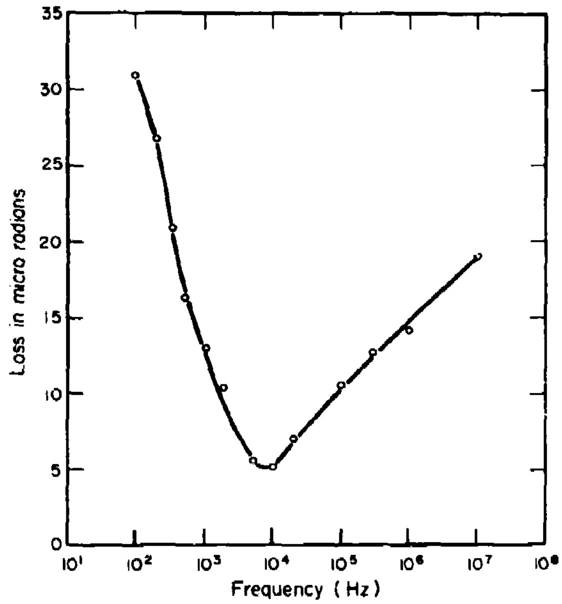
Corning Glass Works

Microwave data on fused silica, Corning 7940, density = 2.20027 g/cm^3. Data with foil taken on one sample at 6.1 GHz, data with paint taken on second sample at 4.3 GHz.





Corning 7940 continued



Corning Lab. No. 119BUC magnetic glass

Corning Glass Works

25°C, 8.52 GHz

κ'	tan δ	κ'_m	tan δ_m
20.8	0.157	1.006	0.372

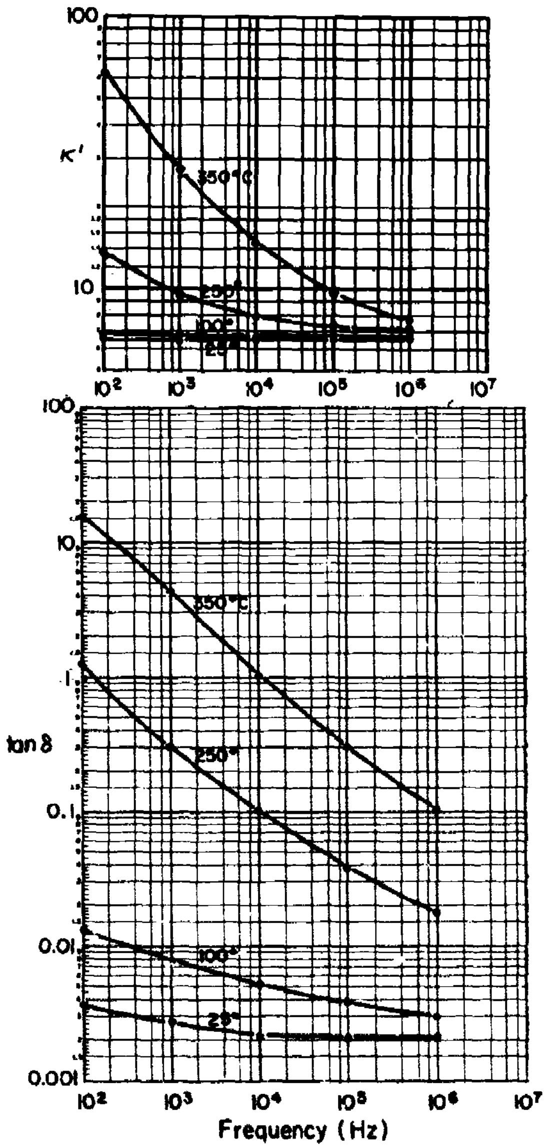
Corning Code 1723 glass

14 GHz			24 GHz		
T°C	κ'	tan δ	T°C	κ'	tan δ
25	6.18	.0069	25	6.13	.0075
85	6.21	.0067	85	6.16	.0075
144	6.24	.0065	155	6.20	.0074
234	6.27	.0063	251	6.24	.0073
305	6.31	.0061	333	6.28	.0074
339	6.33	.0060	419	6.32	.0073
396	6.36	.0059	446	6.35	.0073
464	6.40	.0057	510	6.39	.0074
502	6.43	.0056			

Silica glasses

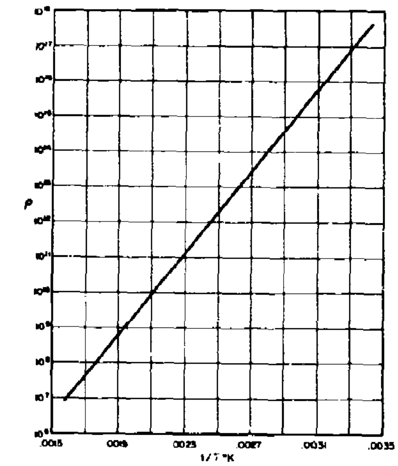
Lancaster

7357

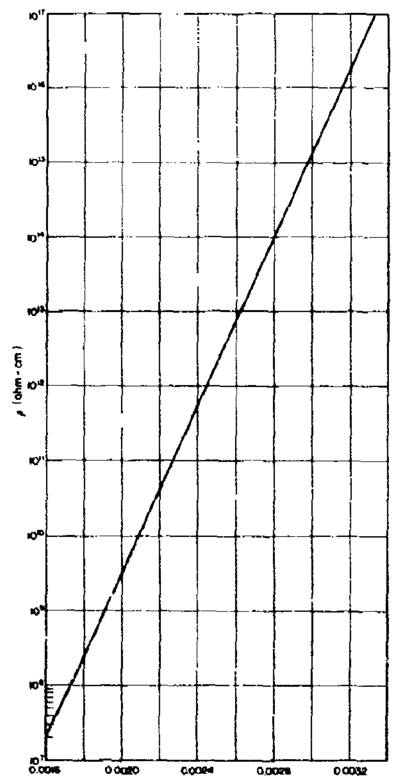


Resistivities measured at 100 Hz

No. 7352

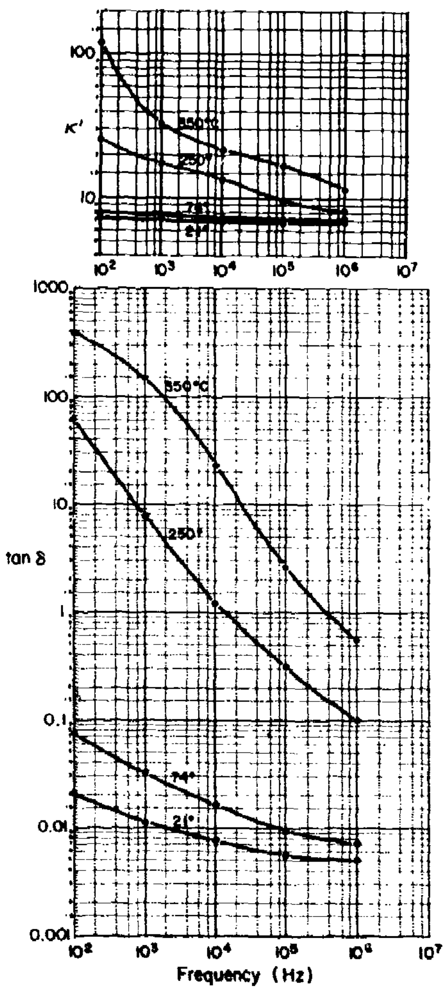


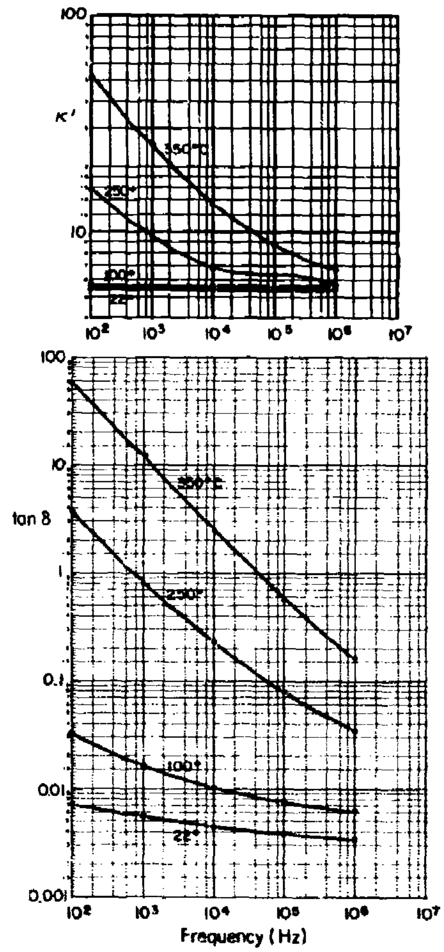
No. 7357



Lancaster glasses (cont.)

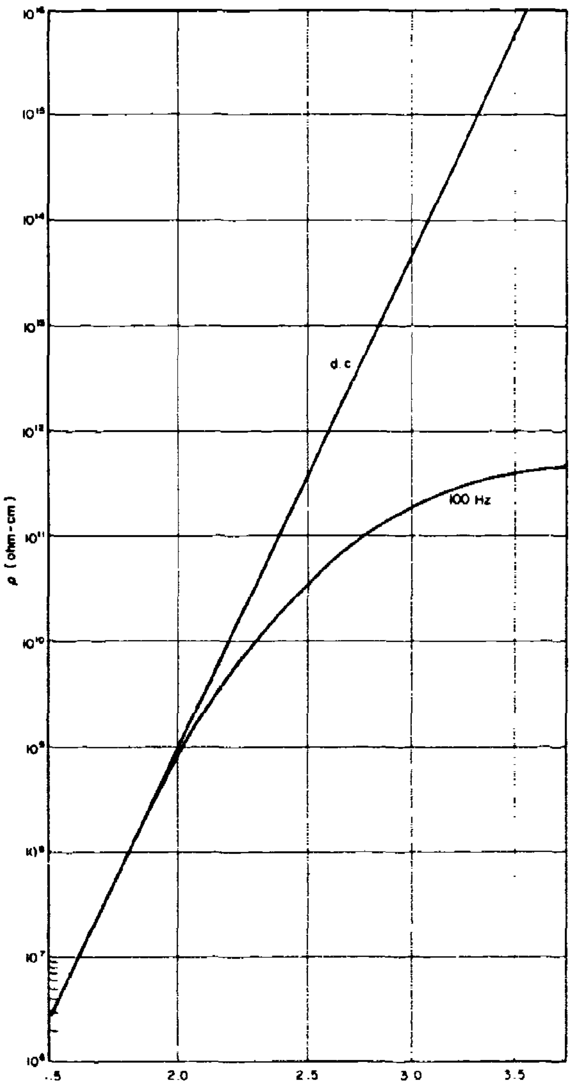
L 1957

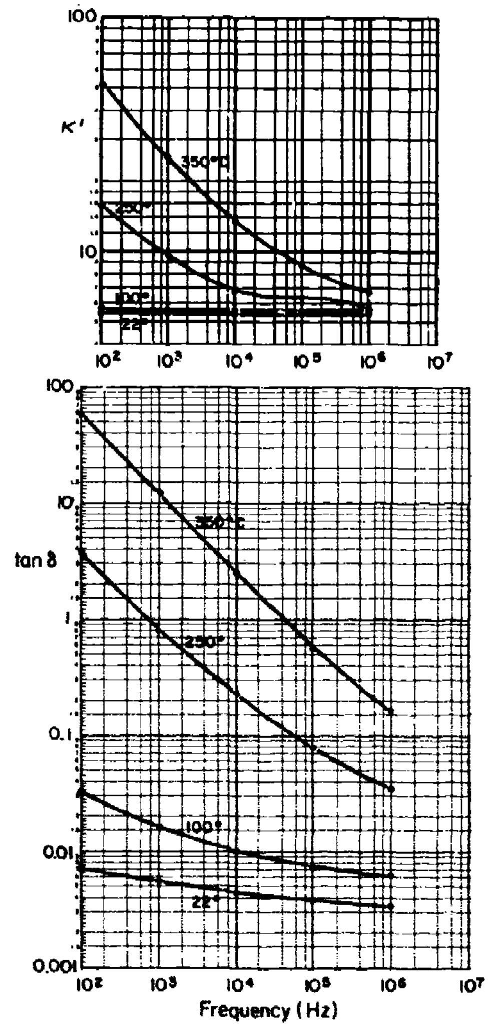




Lancaster glasses (cont.)

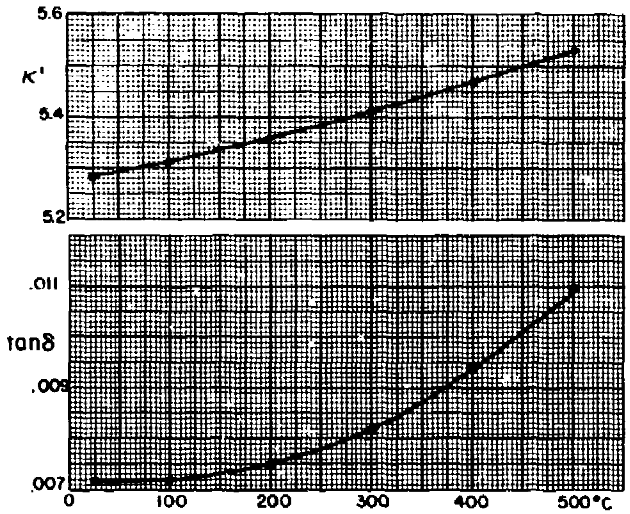
No. L 8100





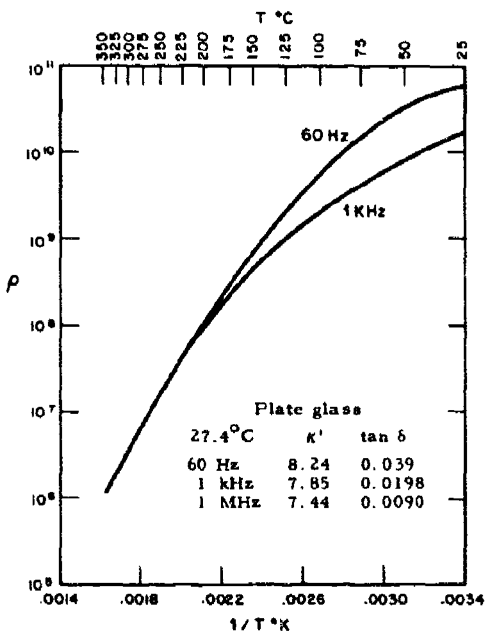
Silicate glasses (cont.)

X 994 Owens-Corning

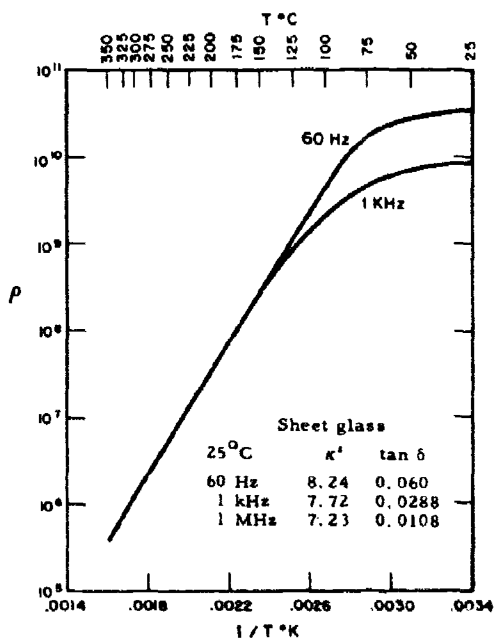


Pittsburgh Plate Glass Co.

Plate glass

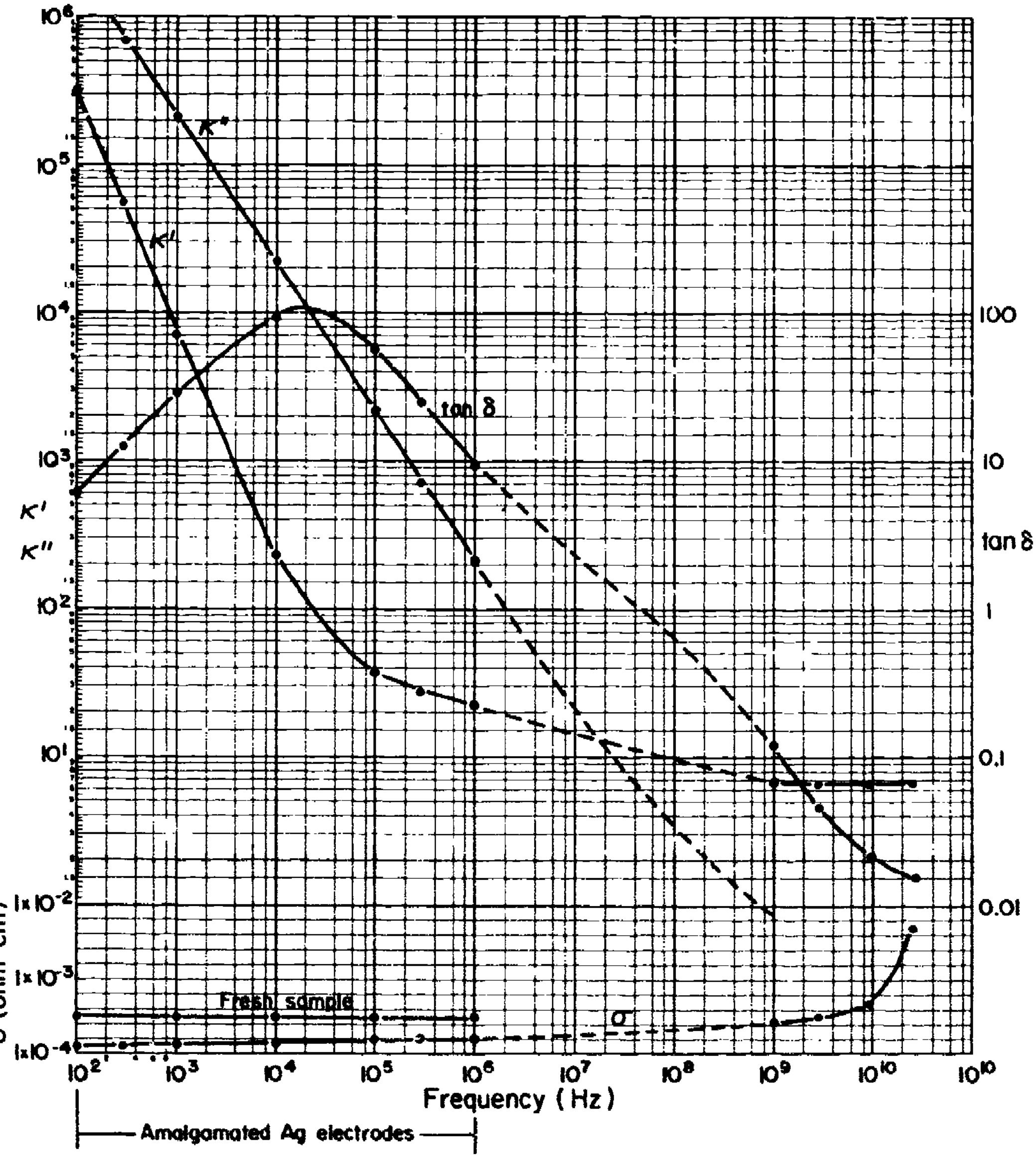


Sheet glass



Silver iodide, pressed powder
at 10,000 psi, 27°C, aged
several weeks unless noted

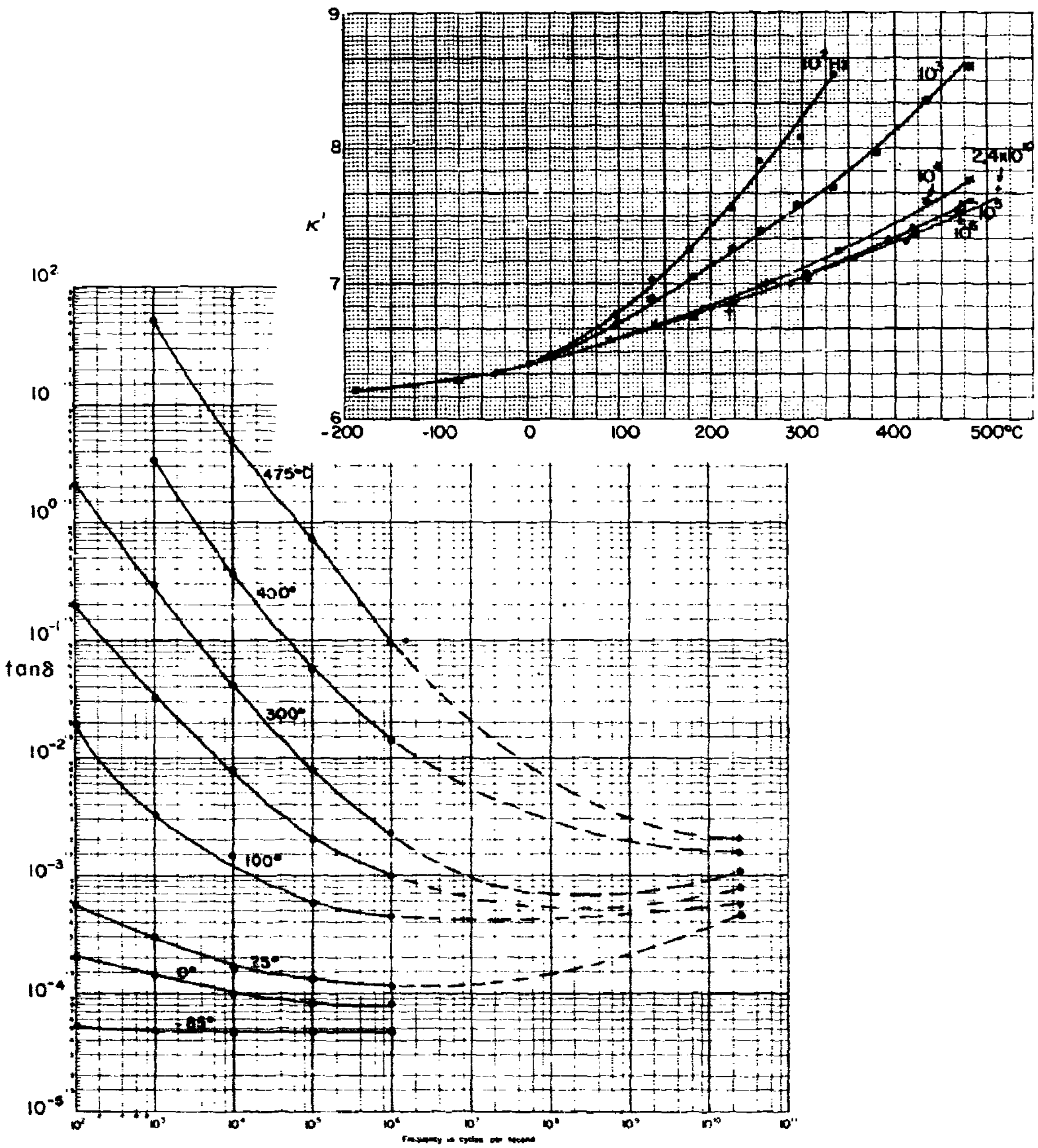
M. I. T., Laboratory for
Insulation Research

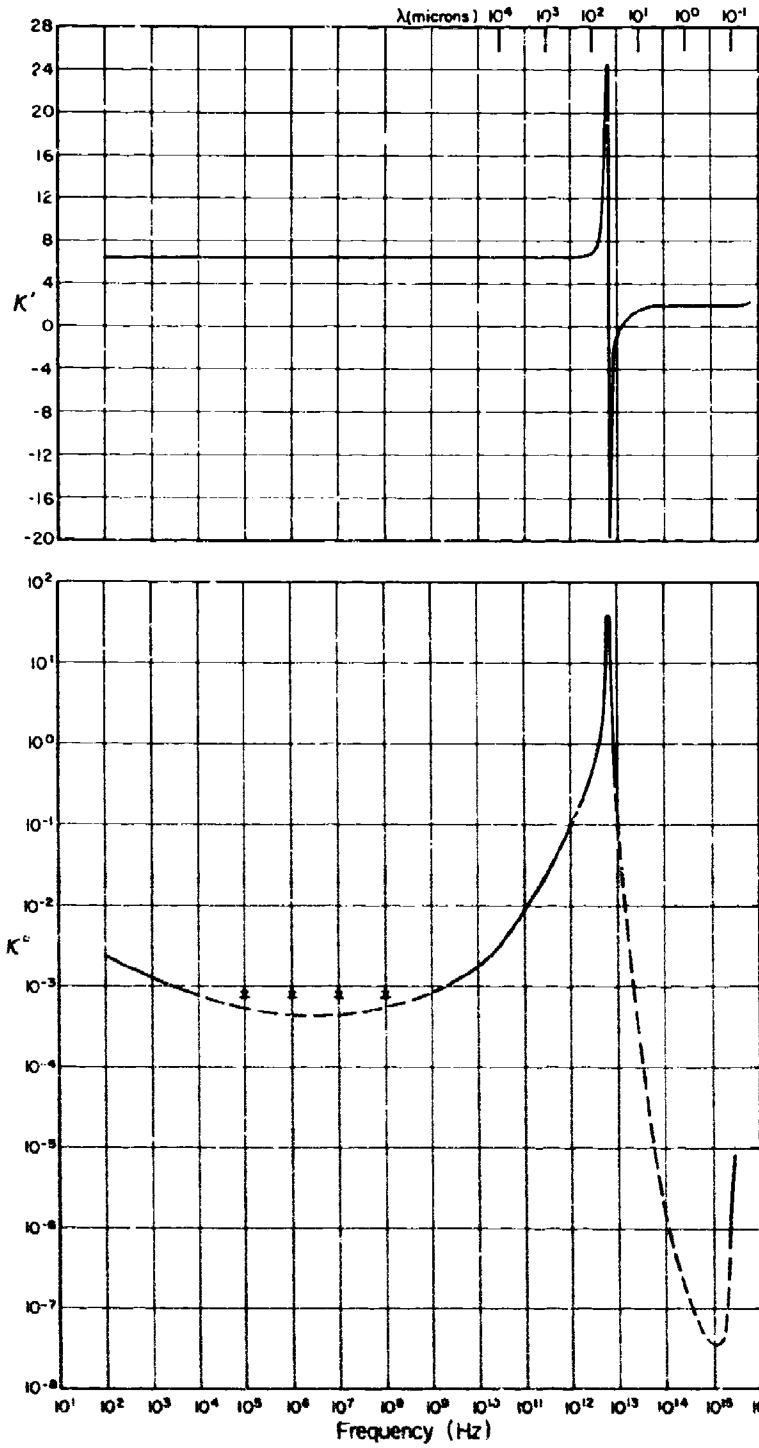


Strontium fluoride

M. I. T. , Crystal Physics Lab.

For more complete data see
K. V. Rao and A. Smakula,
J. Appl. Phys. 37, 319 (1966).





Wide-frequency-range data on SrF_2 crystal. At frequencies above microwaves, reflection data obtained with several optical instruments were combined and Kramer's-Kronig relations used to calculate κ' and κ''.

Thallium halides M.I.T., Crystal Physics Lab.

Material	κ', 25°C 10^6 Hz	κ', 4°K	tan δ, 25°C 10^6 Hz	Activation energy for conduction in eV
TlF pressed	19.7	-	.00015	-
TlCl	31.9	-	.00006	.73
TlBr	30.4	-	.00005	.77
TlI polycrystalline	20.4	20.0	.00024	-
KRS6 $(TlCl)_{.7}$-$(TlBr)_{.3}$	32.2	38.4	.000075	.71
KRS5 $(TlBr)_{.42}$-$(TlI)_{.58}$	32.4	-	.00016	.66
TlI + $CsI_{.01}$	32.5	39.4	.000068	.65

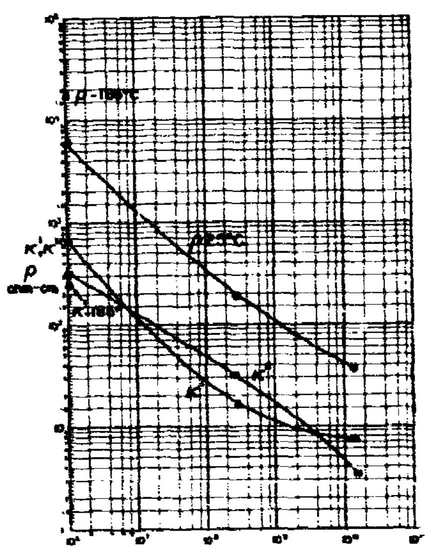
For more complete data see reports under Contract AF 19(628)-395.

Vanadium oxide (V_2O_3) M.I.T., Lab. Ins. Research

Pressed powder samples, -185°C:

f (Hz)	κ' meas.	κ' corr. to full density	Density g/cm^3
10^5	6.52	15.2	2.60
10^6	4.72	14.5	2.28

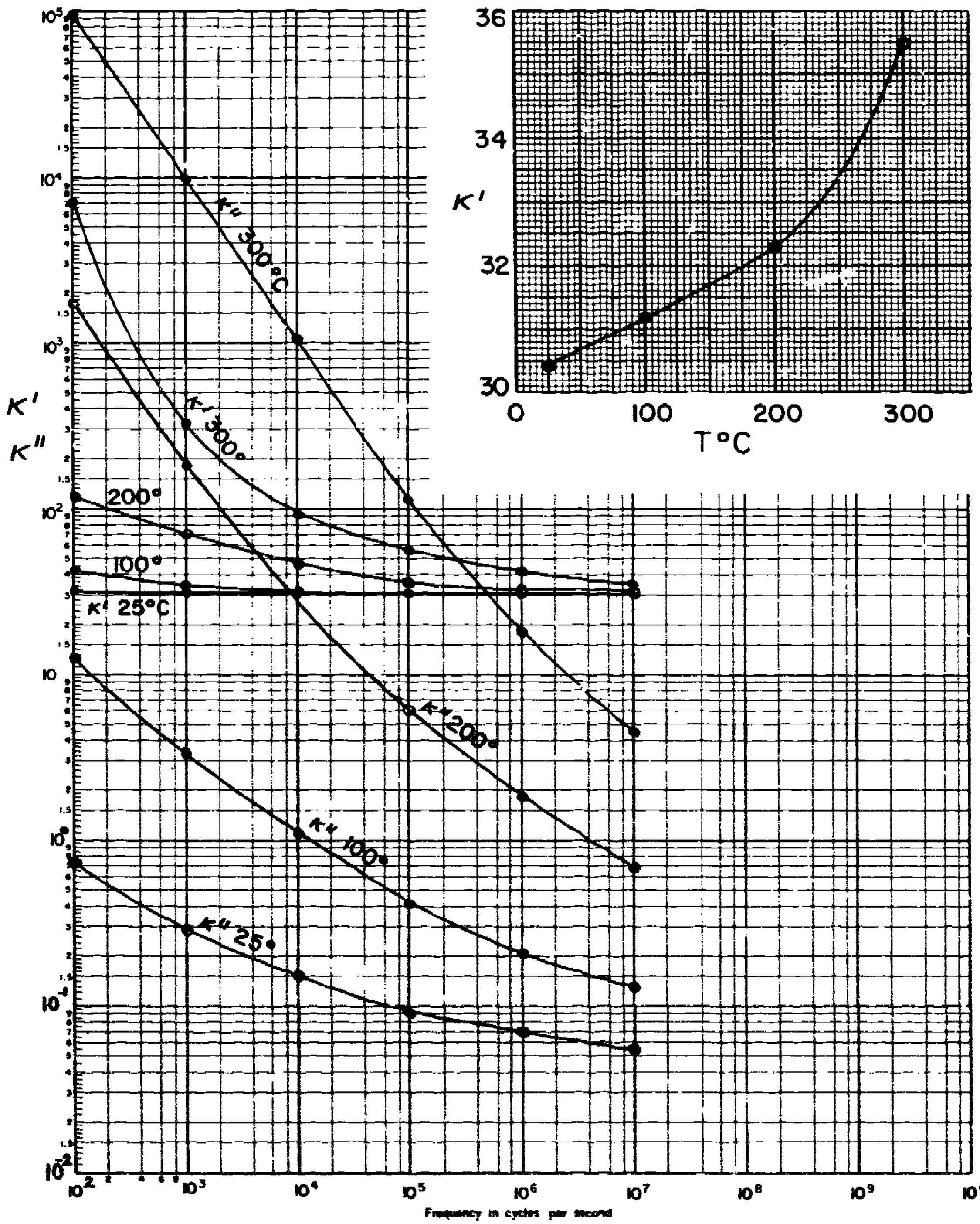
Zinc oxide Airtron Div. of Litton Industries



Measurements of 1 and 300 MHz with electric field ‖ to c axis. At 1.4 GHz field was perpendicular.

Zirconium oxide, "Zircolite" ceramic

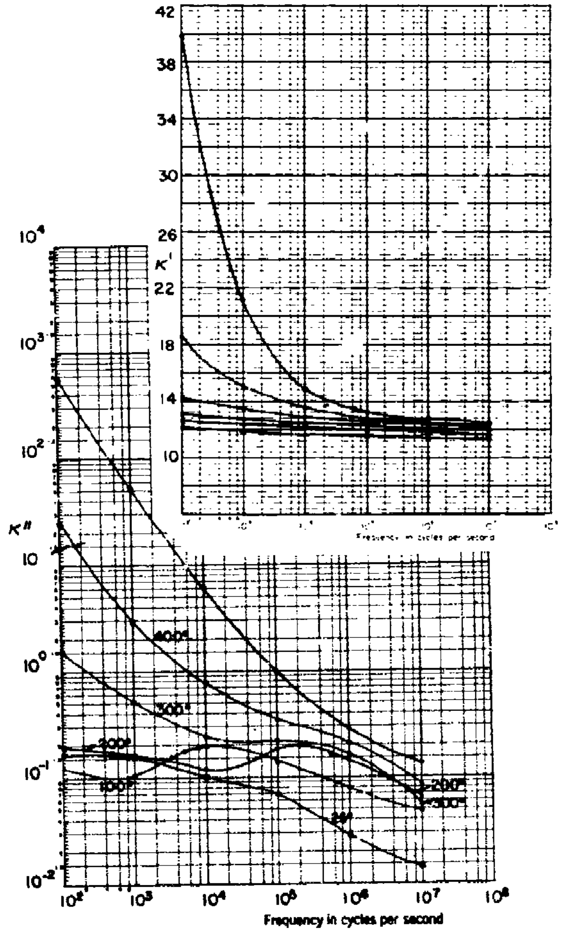
Air Force Materials Laboratory
Wright-Patterson Air Force
Base, Ohio

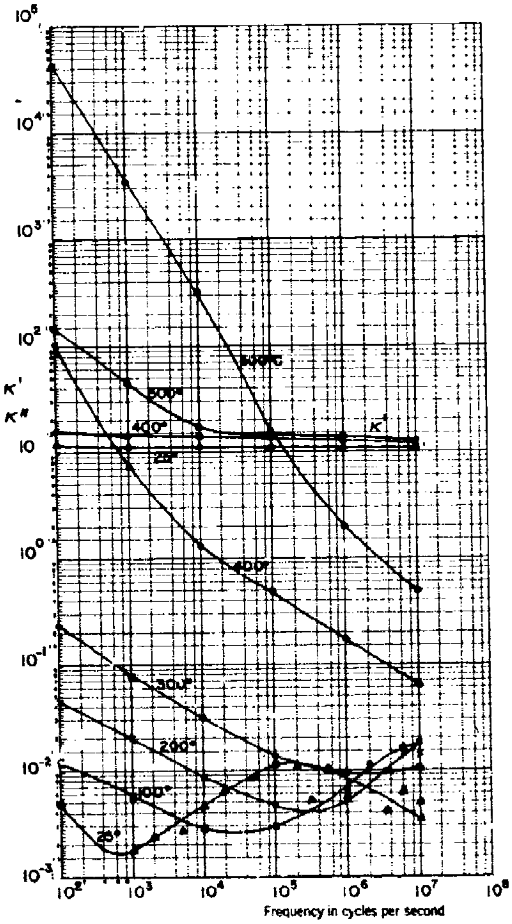


Zirconium silicate (zircon), $ZrSiO_4$,
all samples from one crystal

E || c
Sample 1, run 1
N_2 to 200°C, air to 500°C,
Ag electrodes

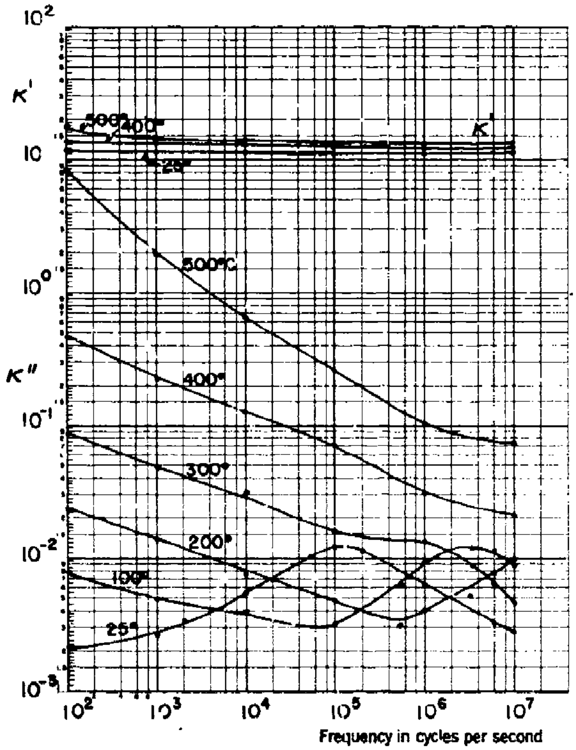
E || c
Sample 2, run 1,
same conditions as for Sample 1

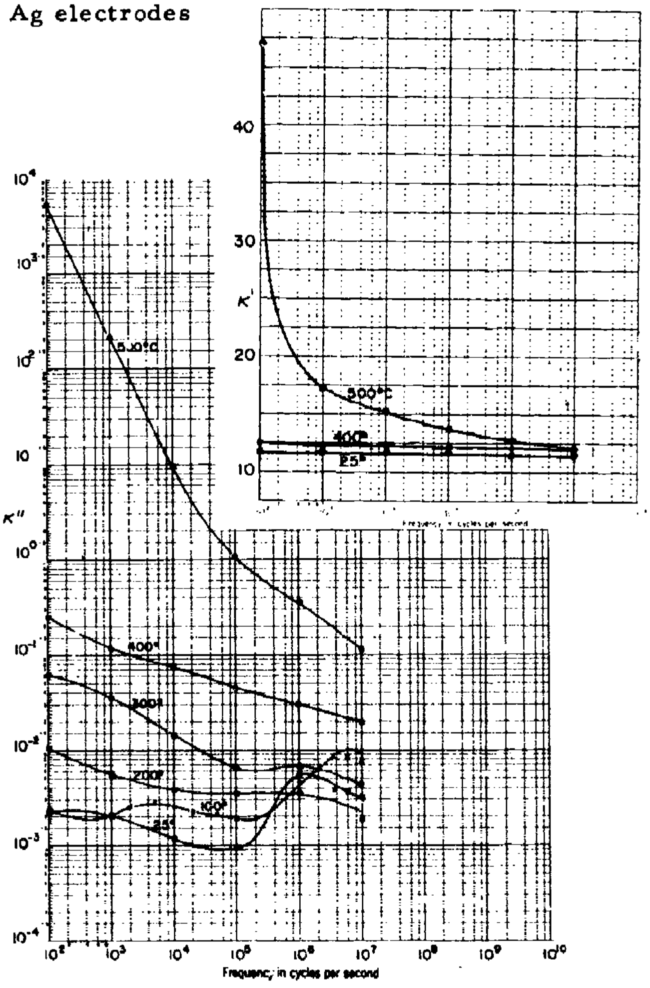




Zircon (cont.)

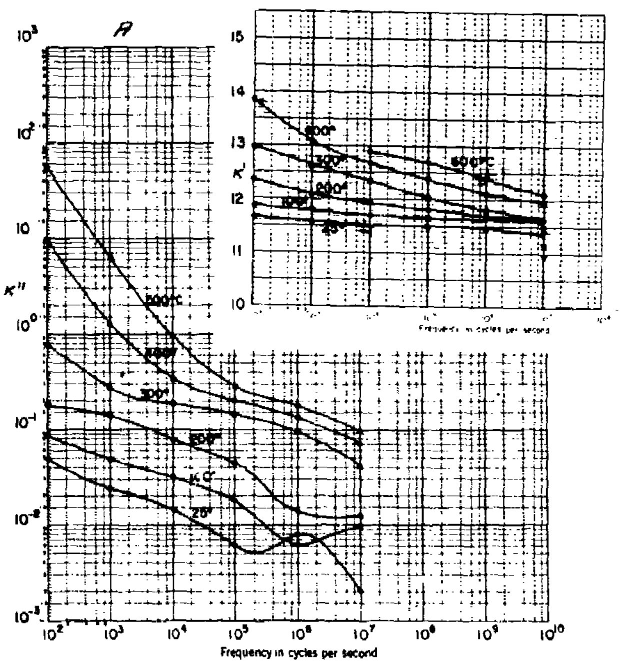
E ∥ c	E ⊥ c
Sample 2, run 2	Sample 1, run 1
Argon atmosphere throughout the run, Ag electrodes	N_2 to 200°C, air to 500°C, Ag electrodes



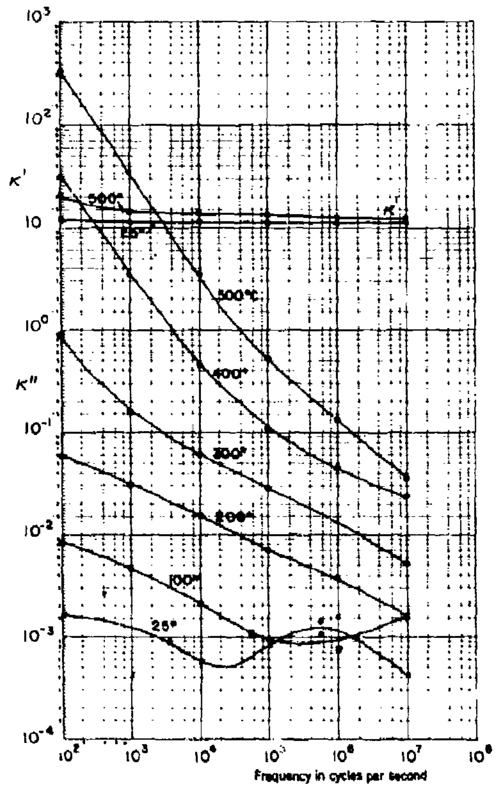


Zircon (cont.)

E ⊥ c
Sample 1, run 2,
N_2 to 500°C,
Ag electrodes



E ⊥ c
Sample 1, run 3,
Ar to 500°C, Pt electrodes



II. Minerals, Rocks, Soils, Miscellaneous Inorganics

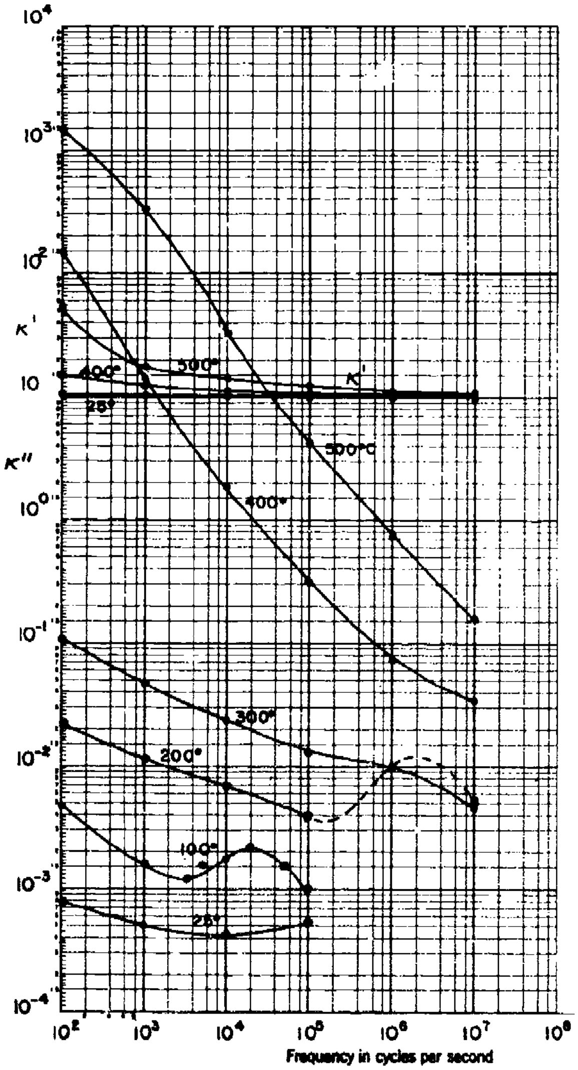
Single crystal minerals

Apatite

E ⊥ c

Sample 1, run 1, 25°C

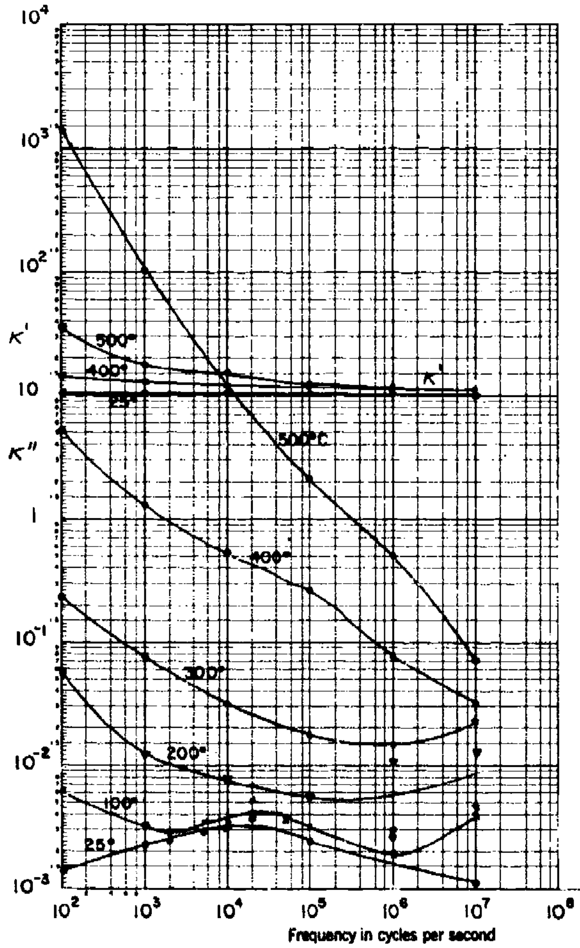
1 MHz, κ' = 10.1



E ⊥ c

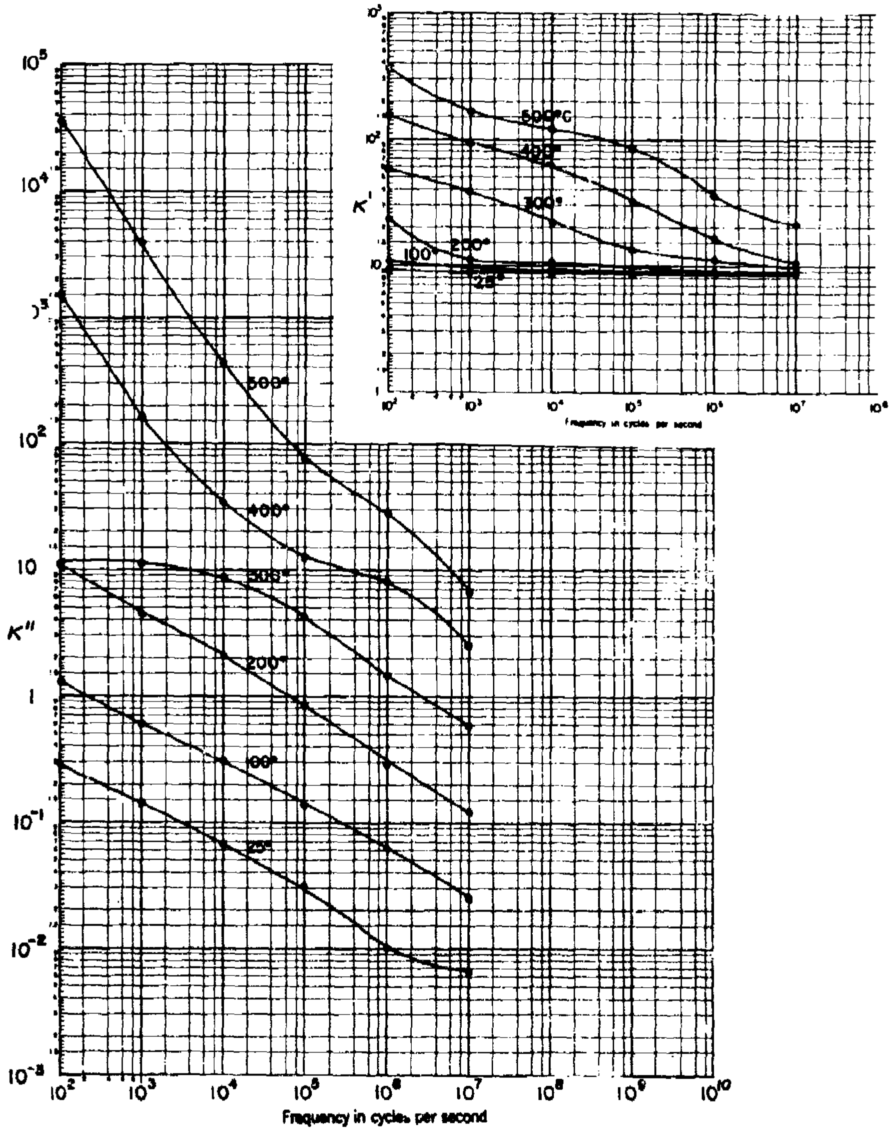
Sample 1, run 2,

repeat of run 1



Apatite (cont.)

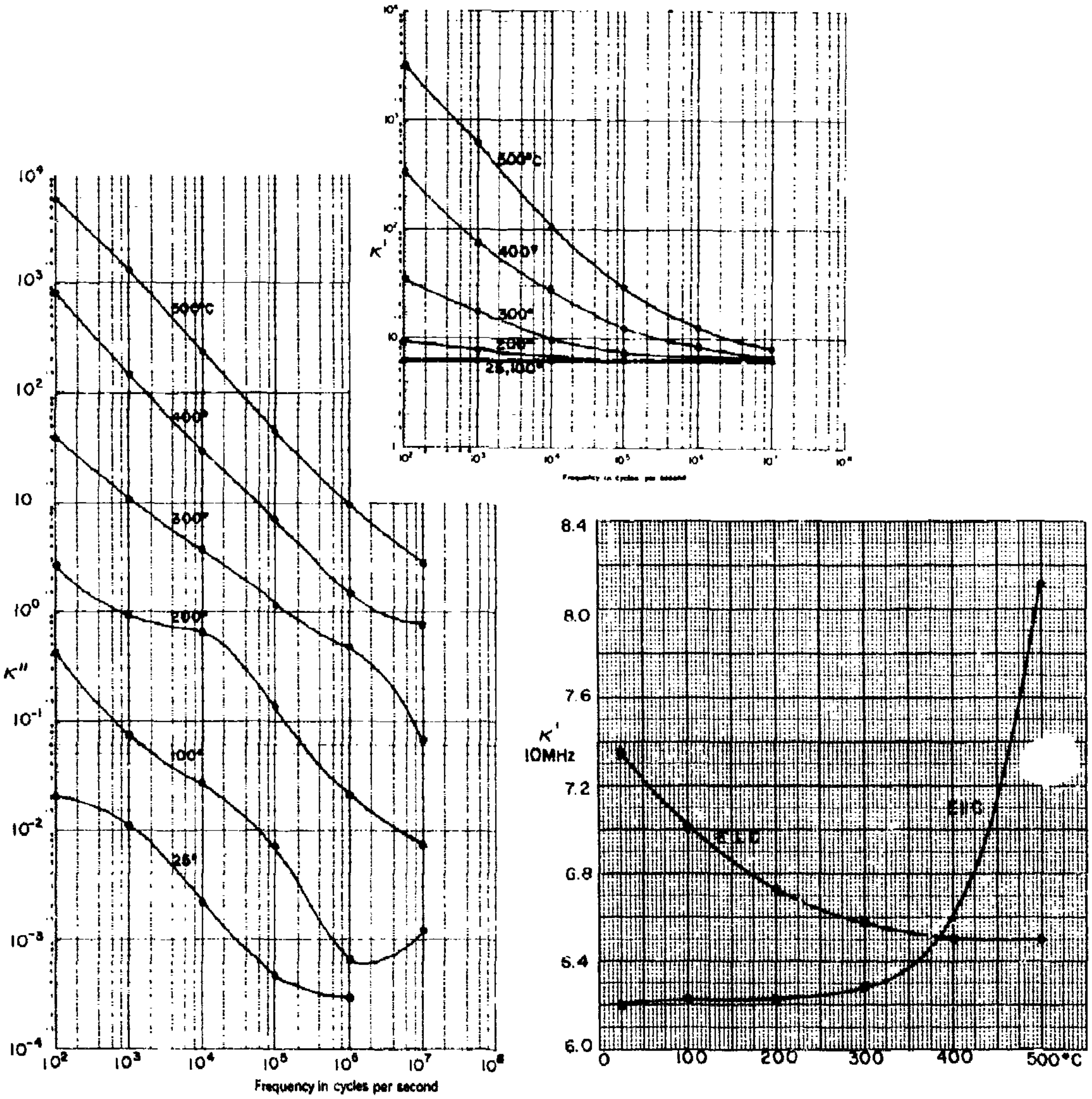
E ‖ c, 25°C, 1 MHz, κ' = 8.58



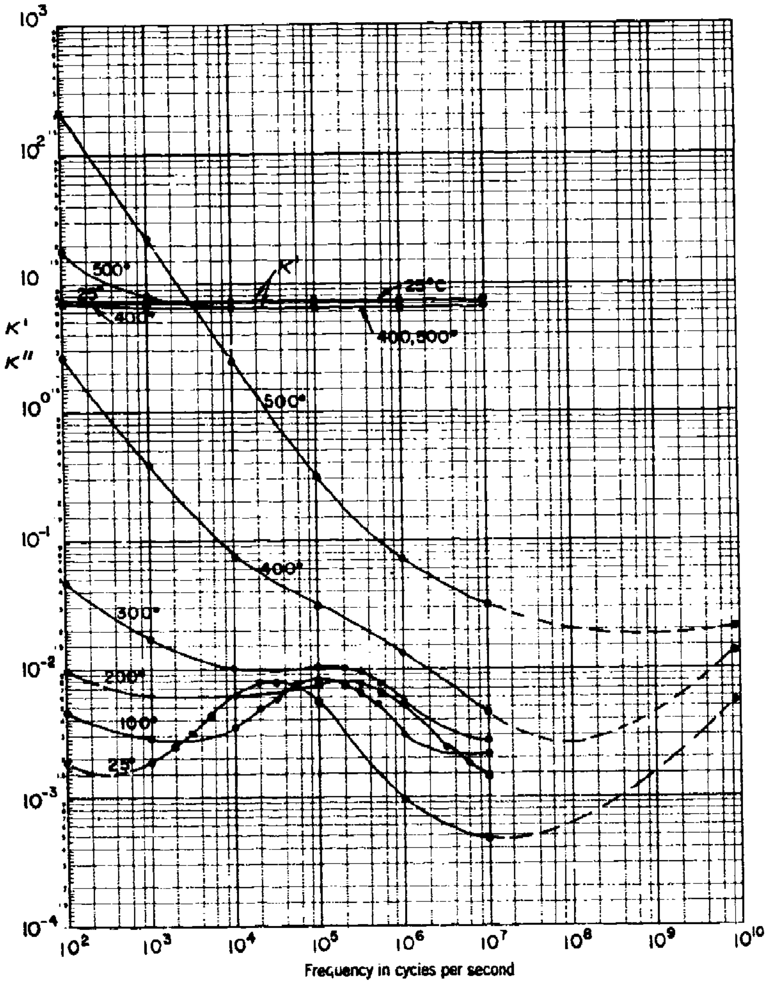
		10^2 Hz	10^3 Hz	10^4 Hz
Astrophyllite				
Unoriented crystal	κ'	15.42	15.17	14.83
	tan δ	0.035	0.021	0.014
Benitoite	κ'	23.8	19.6	19.2
$BaTiS_3O_9$, unoriented cryst.	tan δ	0.374	0.090	0.0195

Beryl

E ‖ c


500°C
400°
300°
200°
25,100°
Frequency in cycles per second
500°C
400°
300°
200°
100°
25°
κ″
Frequency in cycles per second
κ′
10MHz
E ⊥ c
E ‖ c
500°C

Beryl, E ⊥ c

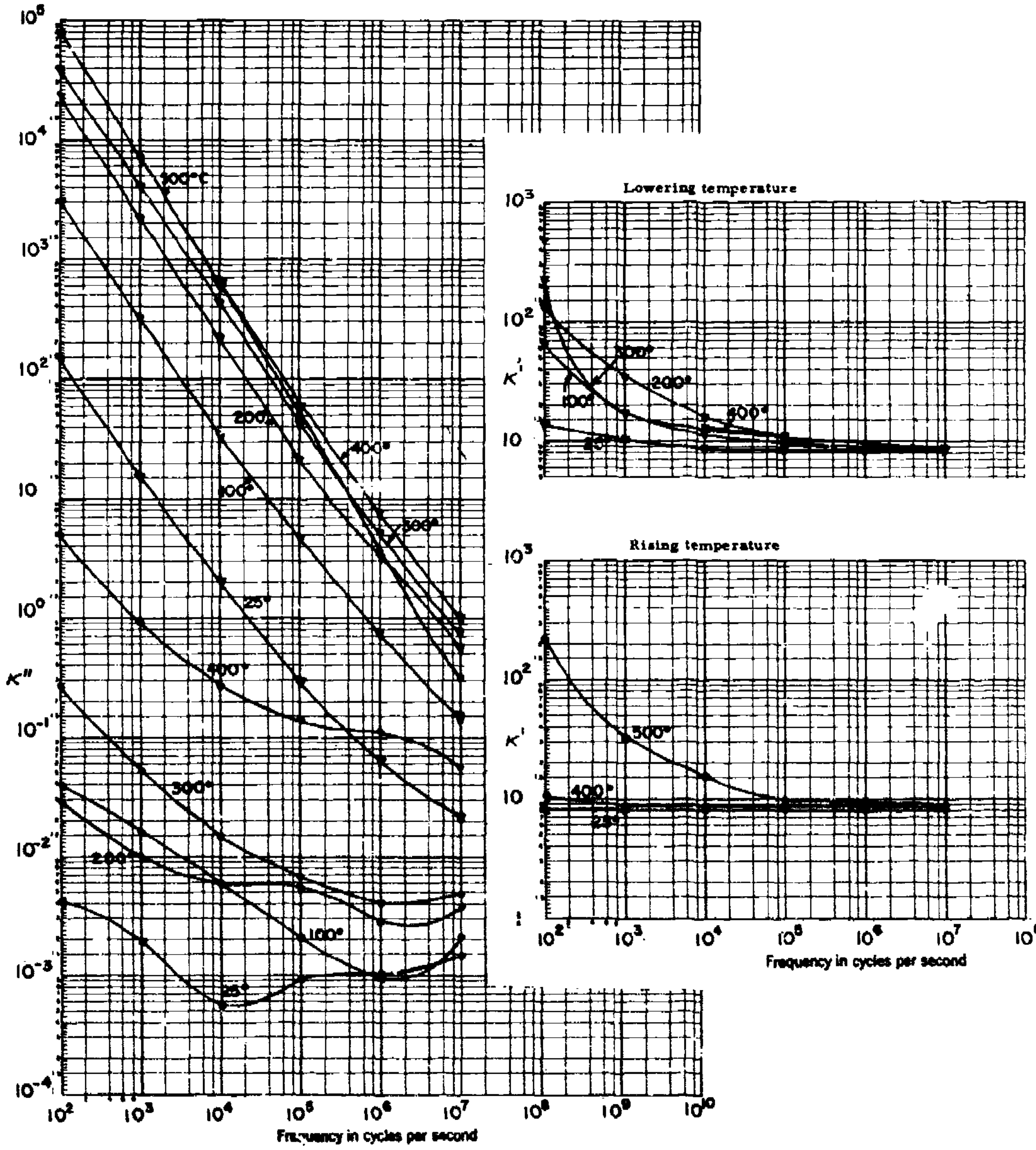


		10^3 Hz	10^4 Hz
Neptunite, $(Na,K)_2(Fe,Mn)(Si,Ti)_5O_{12}$, data on unoriented crystal	κ'	8.33	8.19
	tan δ	0.0335	0.068

Spodumene

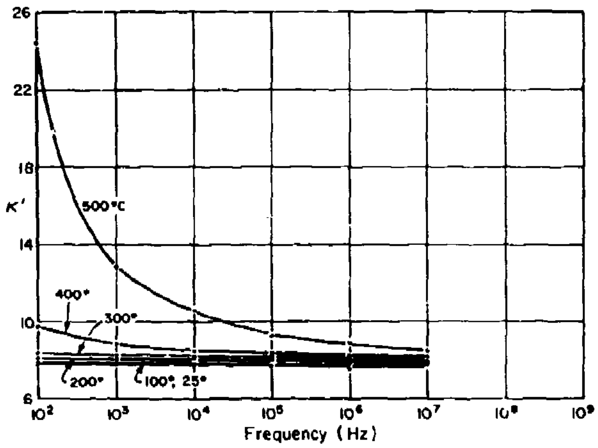
E || a   o rising temperature

∇ lowering temperature

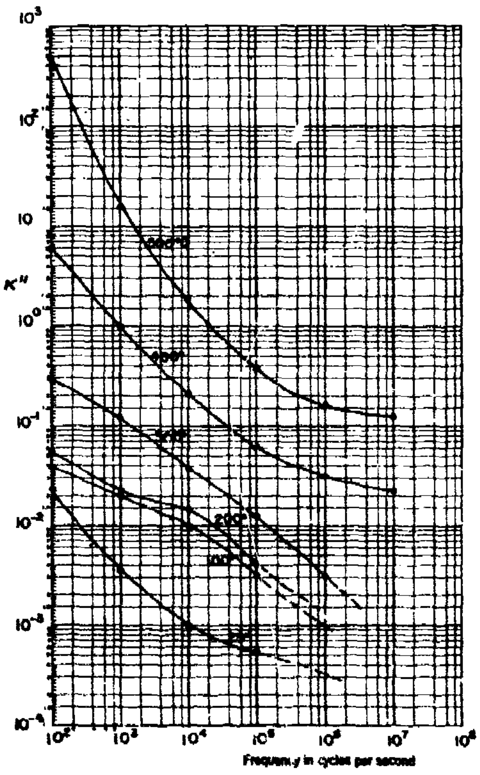


Spodumene (cont.)

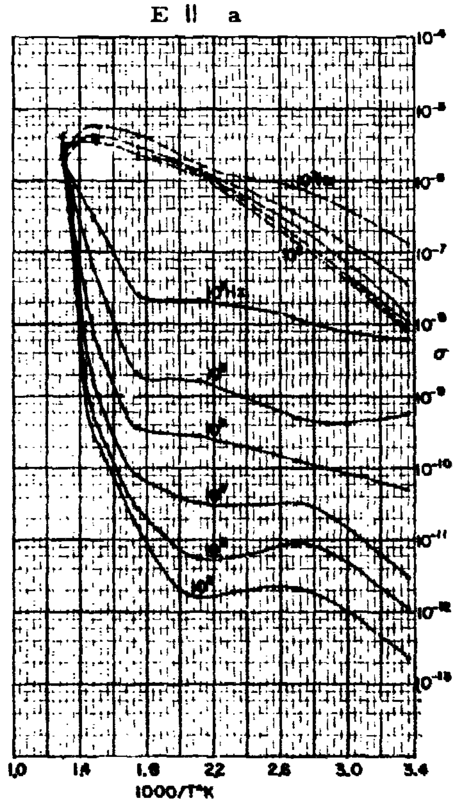
E ∥ b



E ∥ b

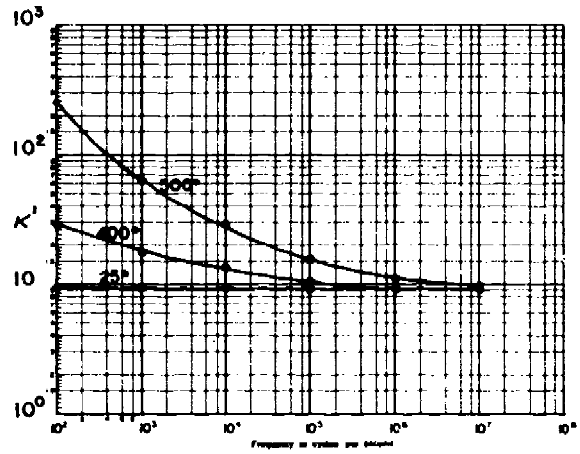


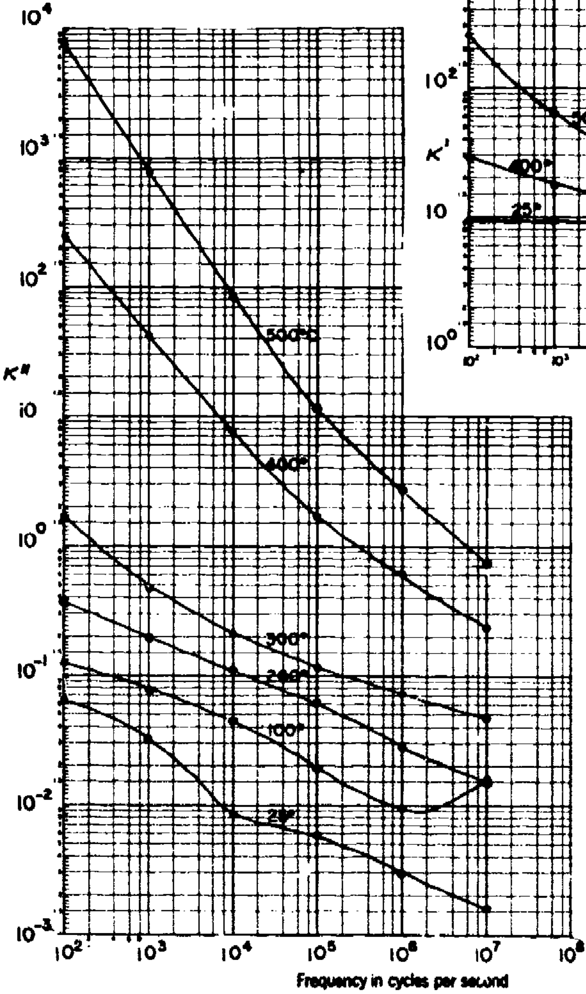
E ∥ a



Spodumene (cont.)

E ∥ c



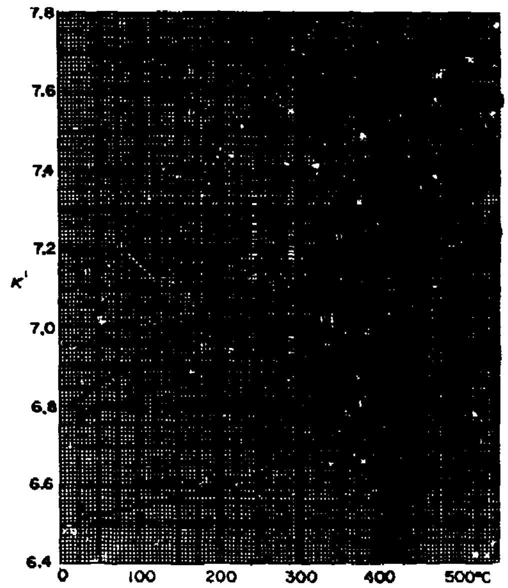


At 10 MHz, 25°C

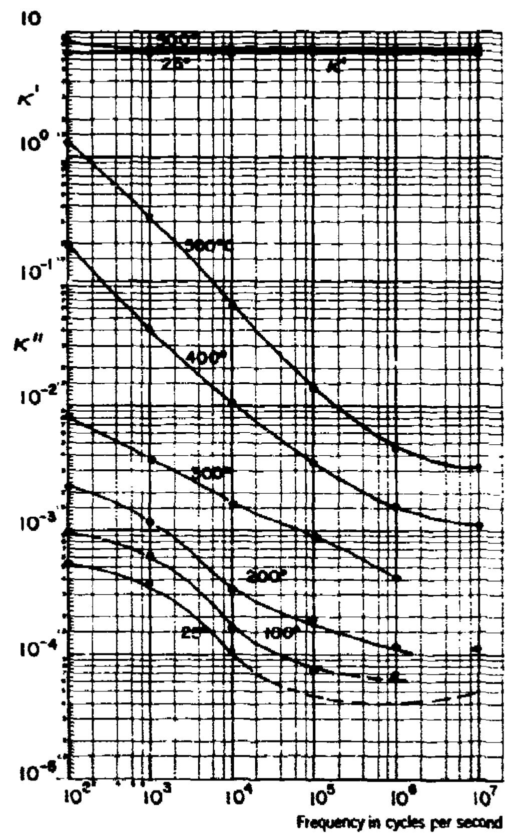
		K'
E ∥	a	8.05
	b	7.82
	c	9.31

Topaz

κ' at 10 MHz

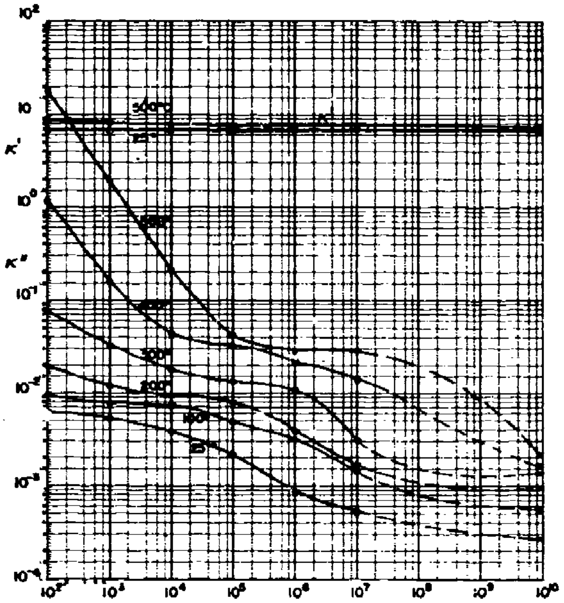


E ‖ a

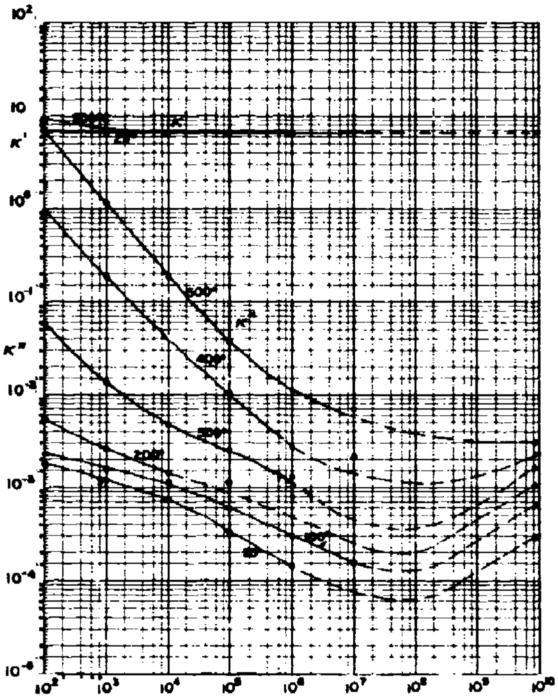


Topaz (cont.)

E ‖ b

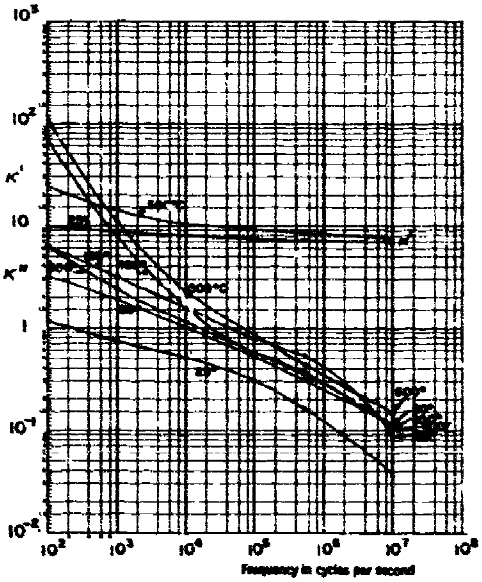


E ‖ c

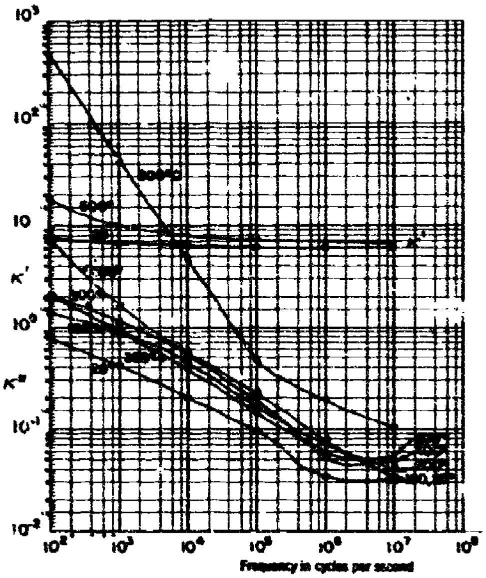


Tourmaline

E ⊥ c, piezoelectrically active at 1 MHz



E ‖ c



Multicrystalline minerals

Halite (rock-like pieces of porous salt), at 50% R.H., 25°C, 14 GHz

Sample	κ'	tan δ	Density (g/cm^3)
1, surface	4.52 - 4.63	.0056 - .0057	1.808
2, "	4.68 - 4.82	.0106 - .0103	1.861
3, "	3.81 - 3.83	.0127 - .0109	1.565
4, "	3.95 - 4.00	.0104 - .0134	1.670
5, 1' down	3.69 - 3.94	.0198 - .0125	1.500
6, "	3.25 - 3.50	.0077 - .0113	1.422
7, 3' "	4.17 - 4.18	.036 - .046	1.646
7, dried	4.12 - 4.19	.0193 - .0206	1.640

Limonite, crushed, density 1.733 g/cm^3

	10^9 Hz		3×10^9	
T°C	κ'	tan δ	κ'	tan δ
25	4.17	.0108	3.73	.046
475	3.65	.0134	3.63	.0193
404	3.62	.0076	3.60	.0113
325	3.61	.0057	3.58	.0084
250	3.61	.0048	3.57	.0073
185	3.60	.0045	3.56	.0064
107	3.58	.0047	3.55	.0059
22	3.56	.0057	3.53	.0055

Sample in equilibrium with room humidity approx. 50%.

Harvard College Observatory

Limonite, 8.52 GHz

Sample 1, coarse, 25°C
κ' = 3.95 - 4.01 depending on rotation
tan δ = 0.18 - 0.059

Sample 2, fine, 25°C

tan δ = 0.0122 - 0.0127

Sample 3

T°C	κ'	tan δ
25	3.82	.0012
510	3.60	.0085
400	3.55	.0047
300	3.52	.0039
200	3.50	.0042
100	3.48	.0043
25	3.49	.0043

Magnesite, crushed powder, hard-packed

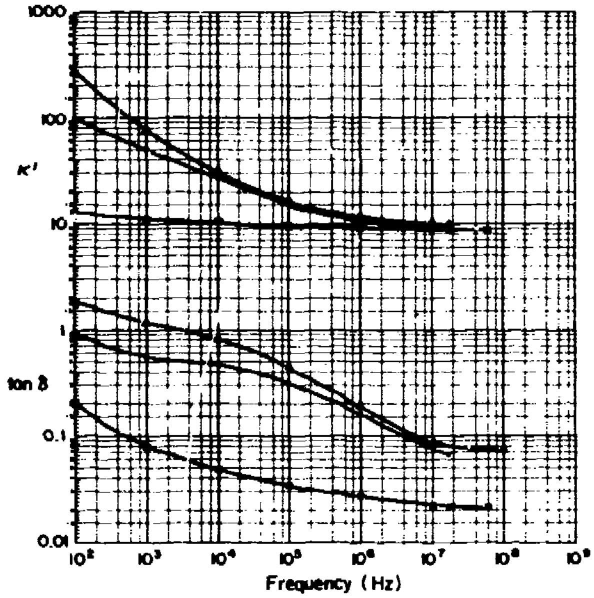
25°C, 50% R.H., 8.52 GHz, κ' = 3.29, tan δ = .0054 - .0059, density 1.11 g/cm^3

Quartz powder, 8.52 GHz, pre-dried in oven at 100°C, density 1.22 g/cm^3

T°K	κ'	tan δ
80	2.446	.0021
200	2.460	.0027
300	2.472	.0028
400	2.483	.0027
500	2.495	.0031
600	2.497	.0035

Rocks

Hawaian, high-density basalt

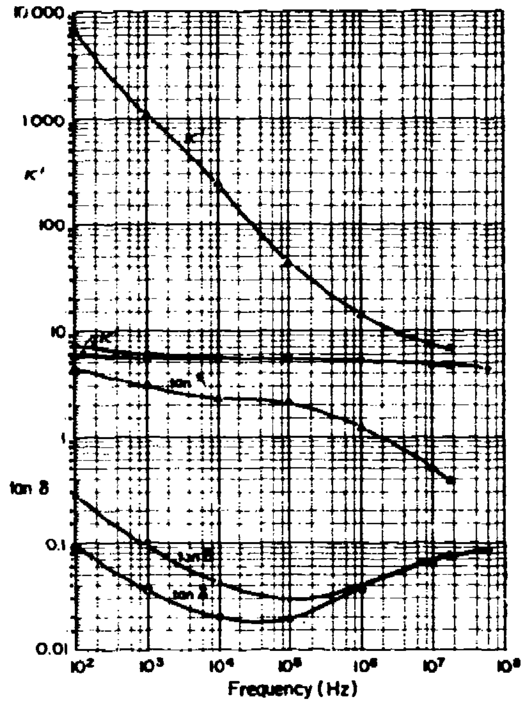


● % H_2O on dry weight basis 0.358
% H_2O on dry volume basis 0.956
density 2.6756 g/cm^3

■ Dry after 3 days in oven at 105°C
density 2.669 g/cm^3

▲ % H_2O on dry weight basis 0.377
% H_2O on dry volume basis 1.005
density 2.677 g/cm^3

Hawaian, low-density basalt



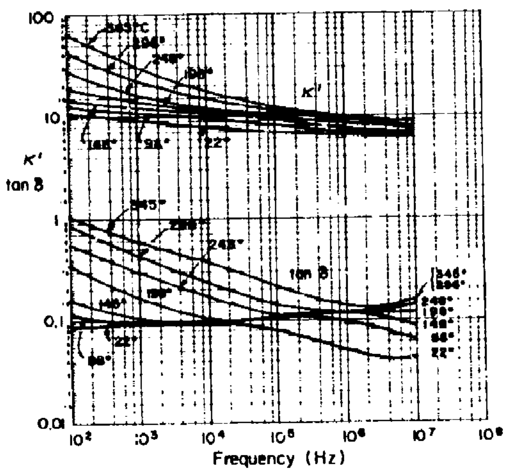
● % H_2O on dry weight basis 0.441
% H_2O on dry volume basis 0.0617
density 1.401 g/cm^3

■ Dry (after 3 days in oven at 105°C
density 1.400 g/cm^3

▲ % H_2O on dry weight basis 2.71
% H_2O on dry volume basis 3.79
density 1.438 g/cm^3

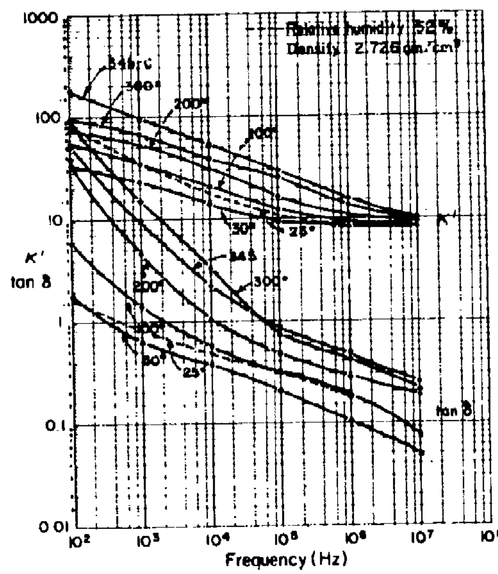
Quincy granite

Density 2.631 g/cm^3
Temp. run in dry N_2



Virginia granite or marble

Temperature run in dry N_2



Quincy granite

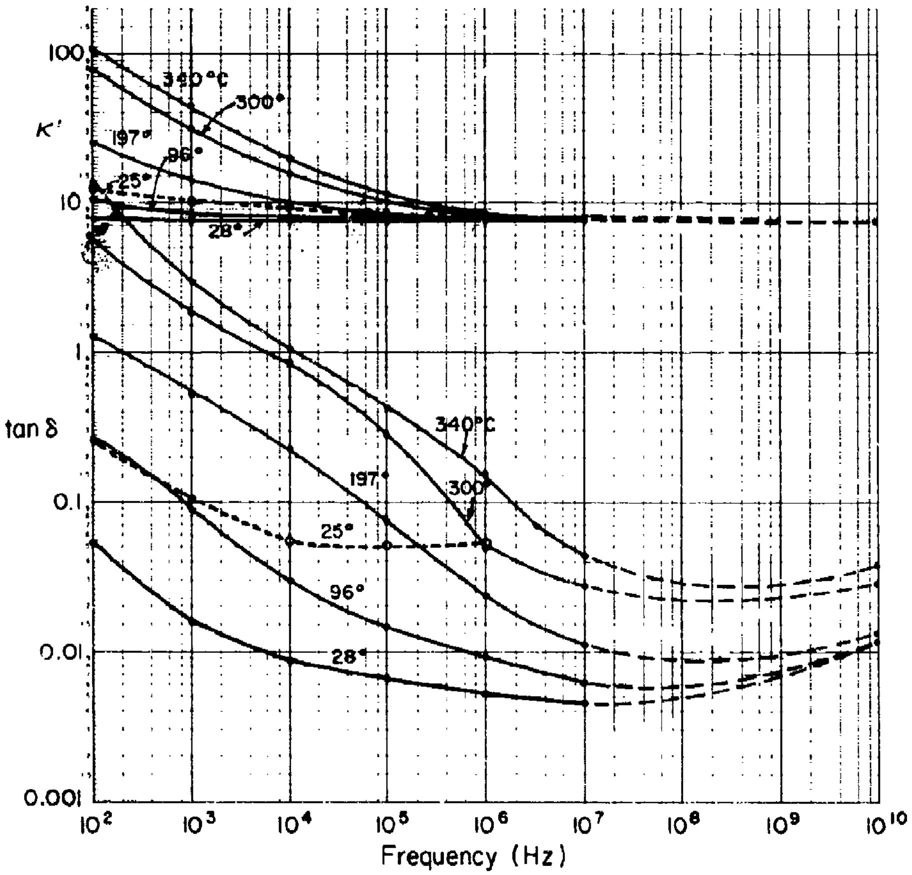
T °C		10^2 Hz	10^3 Hz	10^4 Hz	10^5 Hz
25	κ'	10.5	9.26	8.01	2.06
	tan δ	0.0796	0.0875	0.0875	0.0705
	σ	4.64×10^{-11}	4.5×10^{-10}	3.9×10^{-10}	2.76×10^{-8}
200	κ'	15.4	12.47	11.07	9.78
	tan δ	0.21	0.121	0.088	0.090
	σ	1.797×10^{-10}	8.37×10^{-10}	5.40×10^{-9}	4.88×10^{-8}
400	κ'	64.5	32.9	19.42	12.86
	tan δ	1.02	0.60	0.374	0.252
	σ	3.65×10^{-9}	1.097×10^{-8}	4.03×10^{-8}	1.797×10^{-7}
600	κ'	293	106	42.5	22.0
	tan δ	6.85	2.31	1.03	0.54
	σ	1.114×10^{-7}	1.36×10^{-9}	2.43×10^{-7}	6.60×10^{-7}
800	κ'	4395	238	84	37.4
	tan δ	14.4	9.65	3.05	1.11
	σ	1.116×10^{-6}	1.275×10^{-6}	1.423×10^{-6}	2.30×10^{-6}
1000	κ'		47000	6100	710
	tan		14.0	12.6	12.4
	σ		3.65×10^{-4}	4.26×10^{-4}	4.89×10^{-4}

	1 kHz	
T °C	κ'	σ
26	9.26	4.50×10^{-10}
69	10.3	4.58
105	10.9	4.64
147	11.5	5.31
204	12.51	8.61×10^{-10}
251	14.87	1.85×10^{-9}
305	19.3	3.38×10^{-9}
345	23.4	5.51×10^{-9}
400	32.9	1.09×10^{-8}
466	34.4	9.5×10^{-8}
553	81.3	9.34×10^{-8}
601	106	1.36×10^{-9}
700	172	4.25×10^{-7}
806	243	1.313×10^{-6}
874	26,800	1.84×10^{-4}
996	45,900	3.57×10^{-4}

Virginia Greenstone

Density 2.936 g/cm^3, temperature run in dry N_2

(------) R.H. 52%



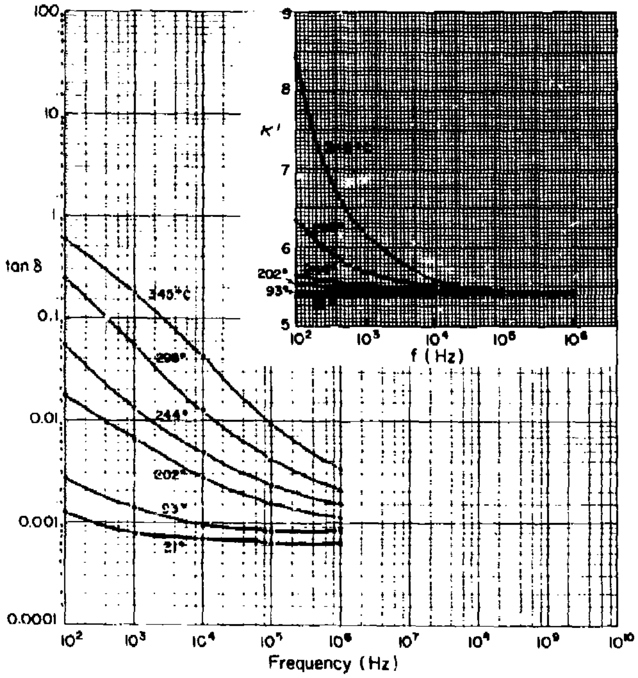
Limestone, from Lucerne Valley — Raytheon

50% R.H., 25°C, 14 GHz

Sample	κ'	tan δ	Density
1	8.21 - 8.45	.0038 - .0080	2.667
2	8.62 - 8.64	.0178 - .0189	2.646

Rhyolite

Density 2.655 g/cm^3, temperature run in dry N_2

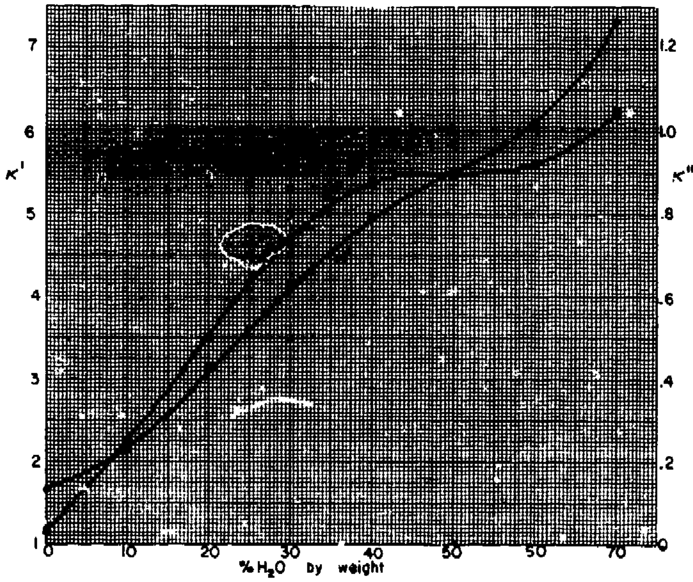


Sandstone, almond, oil-bearing as cored, 25°C Raytheon

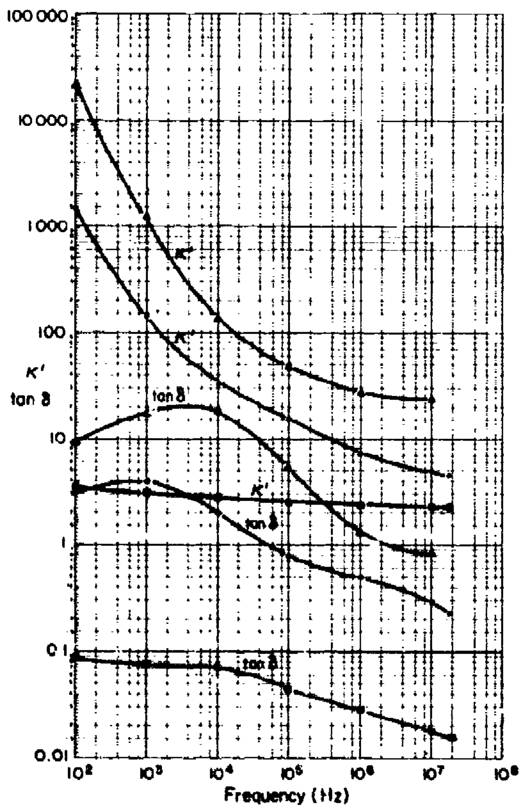
Sample		Frequency in MHz: 1	3	10	60	100
1	κ'	5.64	5.23	4.90	4.55	4.50
	tan δ	0.131	0.104	0.084	0.059	0.049
2	κ'	6.13	6.09	6.07	6.06	6.06
	tan δ	0.0100	0.0084	0.0059	0.0047	0.0051
3	κ'	6.05	6.04	6.01	5.91	5.87
	tan δ	0.0068	0.0079	0.00855	0.0095	0.0097
4	κ'	5.33	5.08	4.92	4.75	4.73
	tan δ	0.060	0.057	0.051	0.036	0.027
5	κ'	5.40	5.16	4.93	4.68	4.61
	tan δ	0.080	0.068	0.058	0.042	0.032
6	κ'	22.9	11.24	9.20	6.60	6.20
	tan δ	1.88	1.39	0.68	0.338	0.29
7	κ'	6.15	6.12	6.10	6.04	6.00
	tan δ	0.0088	0.0093	0.0096	0.0102	0.0105

Soils

Fullers Earth, at 8. 52 GHz



Hawaian



● % H_2O on weight basis 20.0

% H_2O on volume basis 14.4

Density 0. 8634 g/cm^3

■ Dry after 3 days in oven at 105°C

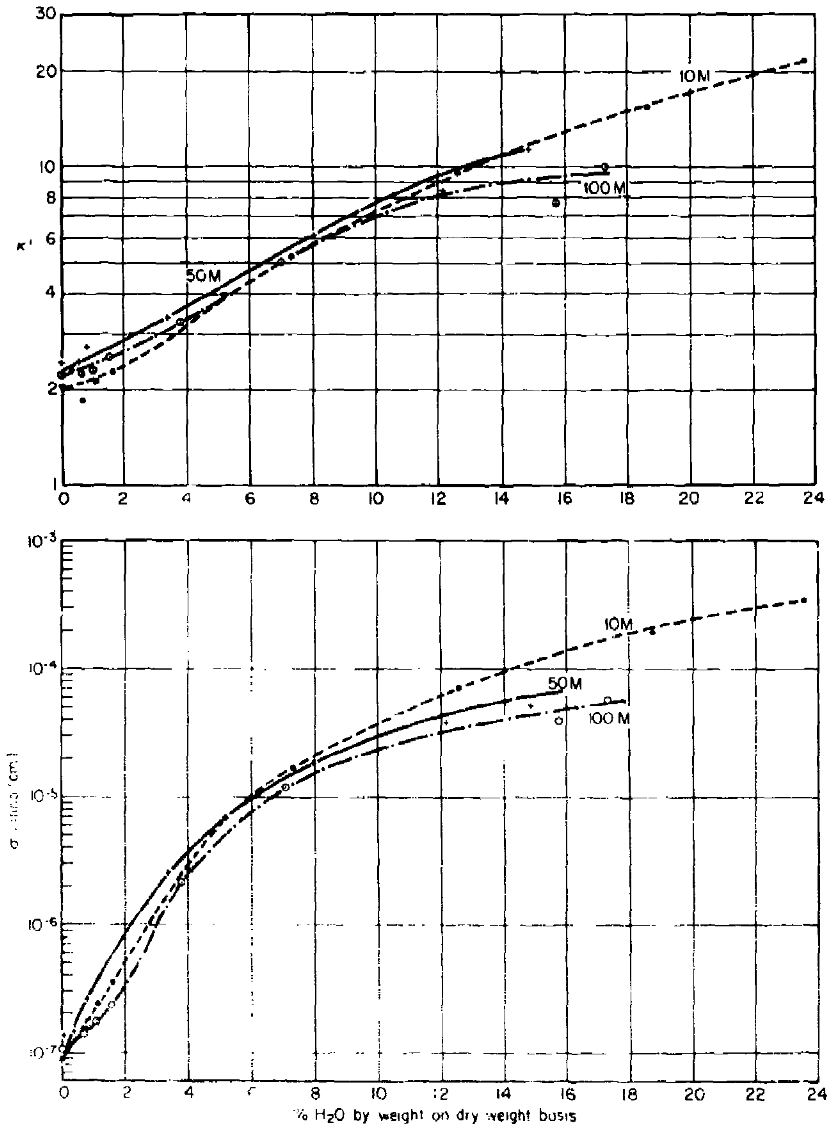
Density . 7627 g/cm^3

▲ % H_2O on dry weight basis = 72. 27

% H_2O on volume basis + 50. 60

Density 1. 2133 g/cm^3

Mass. loams, at 10 MHz, 25°C



Desert sand (Raytheon)

15% R. H., 25°C, 14 GHz

κ' = 2.[illegible]

tan δ = 0.011[illegible]

Density = 1.[illegible]3 g/cm^3

DIELECTRIC CONSTANTS

Sample, Source	Density (g/cm^3)	Temp. (^{o}/C)	Frequency in MHz 110*	150	300	500	1000	2700
Dartmouth		-1	3.22	3.21	3.20	3.20	3.20	3.201
Firm ice No. 12		5	3.21	3.20	3.20	3.20	3.20	3.195
		10	3.20	3.19	3.19	3.19	3.19	3.188
		20	3.18	3.18	3.18	3.18	3.18	3.175
	0.898	30	3.17	3.16	3.16	3.16	3.16	3.163
		40	3.15	3.15	3.15	3.15	3.15	3.151
		50	3.14	3.14	3.14	3.14	3.14	3.139
		60	3.13	3.13	3.13	3.13	3.13	3.129
Dartmouth		-1	3.41	3.38	3.34	3.31	3.28	
Sea ice No. 14		5	3.33	3.31	3.29	3.27	3.26	
		10	3.28	3.26	3.25	3.24	3.24	
		15	3.26	3.24	3.24	3.23	3.22	
		20	3.23	3.22	3.21	3.20	3.20	3.197
		25	3.22	3.21	3.20	3.19	3.19	3.184
	0.917	30	3.21	3.20	3.19	3.18	3.17	3.173
		40	3.19	3.18	3.17	3.16	3.16	3.159
		50	3.18	3.17	3.16	3.15	3.15	3.144
		60	3.15	3.15	3.14	3.14	3.14	3.133
Tuto Tunnel		-1	3.22	3.21	3.20	3.20	3.20	3.197
		5	3.20	3.19	3.19	3.19	3.19	3.189
		10	3.19	3.18	3.18	3.18	3.18	3.182
		20	3.17	3.17	3.17	3.17	3.17	3.170
	0.902	30	3.16	3.16	3.16	3.16	3.16	3.159
		40	3.15	3.15	3.15	3.15	3.15	3.149
		50	3.14	3.14	3.14	3.14	3.14	3.138
		60	3.13	3.13	3.13	3.13	3.13	3.129
Little America		-1	3.09	3.08	3.07	3.07	3.07	3.065
		5	3.07	3.06	3.06	3.06	3.06	3.057
		10	3.06	3.05	3.05	3.05	3.05	3.050
		20	3.04	3.04	3.04	3.04	3.04	3.038
	0.881	30	3.03	3.03	3.03	3.03	3.03	3.025
		40	3.01	3.01	3.01	3.01	3.01	3.012
		50	3.00	3.00	3.00	3.00	3.00	3.000
Artic		-1	2.90					2.880
		5	2.89					2.875
		10	2.88					2.870
		20	2.86					2.861
	0.835	30	2.85	2.85	2.85	2.85	2.85	2.852
		40	2.85	2.85	2.85	2.84	2.84	2.844
		50	2.84	2.84	2.84	2.84	2.84	2.835
		60	2.83	2.83	2.83	2.83	2.83	2.827

LOSS TANGENT

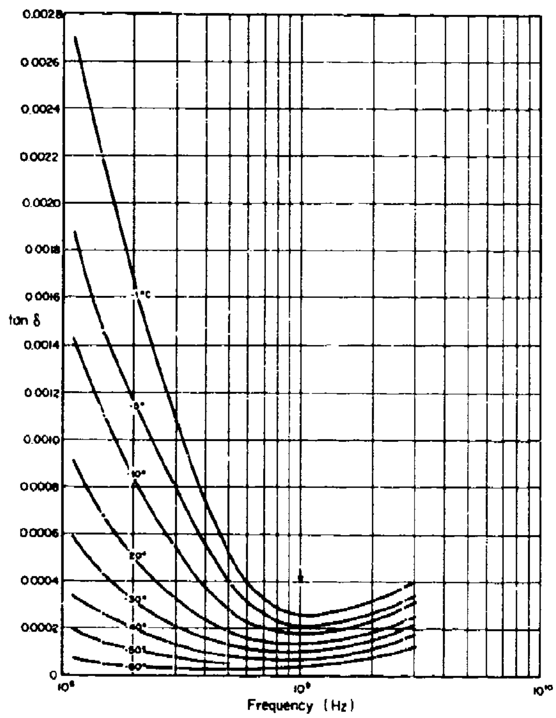
Sample, Source	Temp. (°/C)	Frequency in MHz 110*	150	300	500	1000	2700
Dartmouth No. 12	-1	.0030	.0022	.00108	.00052	.0004	.00038
	5	.0019	.00144	.00076	.00040		.00034
	10	.00145	.00110	.00055	.00028		.00030
	20	.00092	.00068	.00033	.00019		.00024
	30	.00059	.00043	.00021	.00013		.00020
	40	.00034	.00026	.00013	.00008		.00016
	50	.00020	.00014	.00008	.00005		.00014
	60	.00008	.00005	.00003	.00003		.00013
Dartmouth No. 14	-1	.039	.037	.0225	.0200	.0122	
	5	.026	.025	.0200	.0130	.0080	
	10	.0195	.0190	.0145	.0097	.0067	
	15	.017	.0157	.0107	.0082	.0054	
	20	.015	.0130	.0091	.0068	.0045	.0044
	25	.013	.0106	.0067	.0047	.0030	.0029
	30	.010	.0080	.0048	.0033	.00205	.00185
	40	.0058	.0045	.0026	.0017	.00112	.00065
	50	.0028	.0023	.0015	.00098	.00062	.00030
	60	.0014	.0012	.00078	.00054	.00035	.00016
Tuto Tunnel	See data for Dartmouth No. 12 (no measurable difference)						
Little America	-1	.0049	.0037	.0018	.00106	.00054	.00038
	5	.0035	.0026	.0013	.00072	.00037	.00032
	10	.00286	.00217	.00108	.00056	.00025	.00027
	20	.0020	.00154	.00078	.00038	.00018	.00024
	30	.00146	.00116	.00057	.00029	.00014	.00020
	40	.00105	.00085	.00044	.00025	.00013	.00014
	50	.00076	.00057	.00030	.00021	.00012	-

* 110 MHz values are extrapolated, not measured.

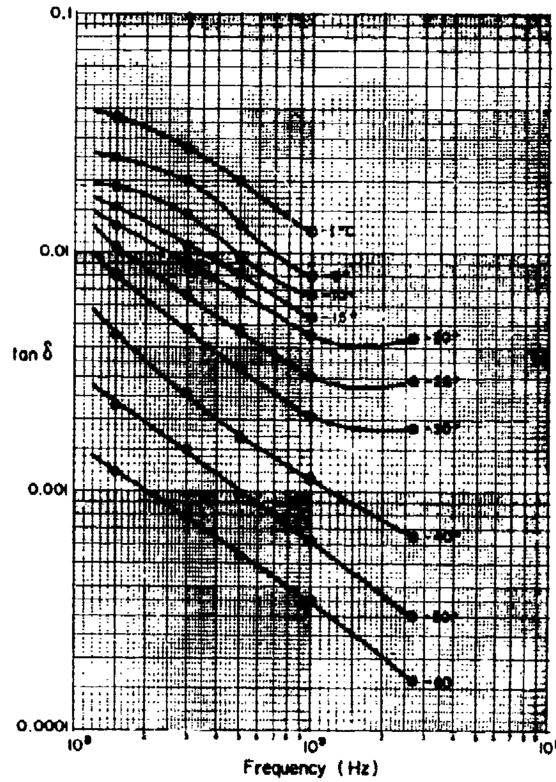
Sample, Source	Temp. (°/C)	110	150	300	500	1000	2700
Artic	-1			-			.00033
	5			-			.00029
	10			Cooling failed, sample melted			.00024
	20			-			.00018
	30			.00045			.00016
	40			.00032			.00014
	50			.00022			.00013
	60			.00015			.00013

Ices

Dartmouth No. 12

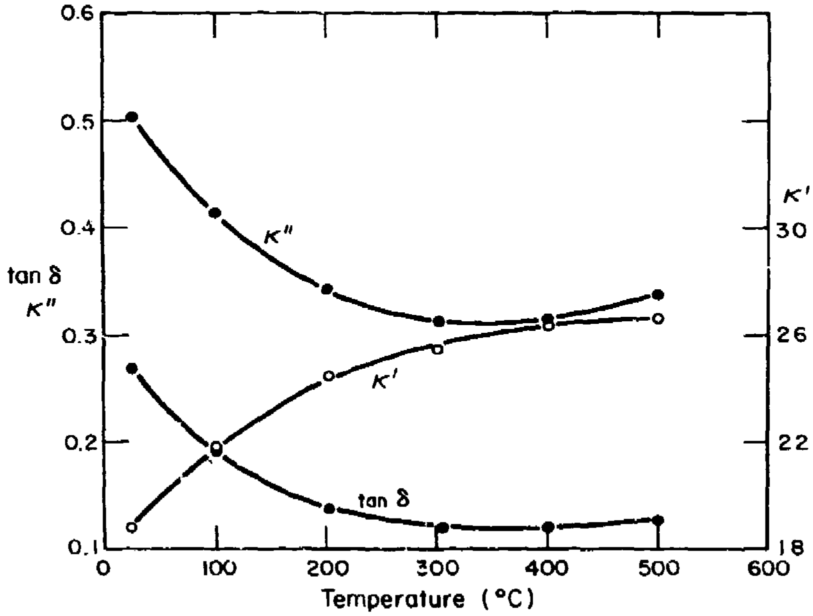


Sea ice



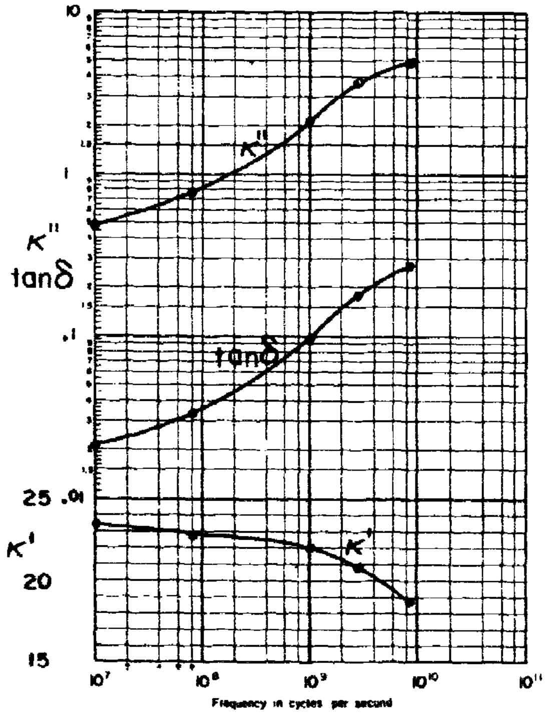
CFI 1003 Ceramics for Industry

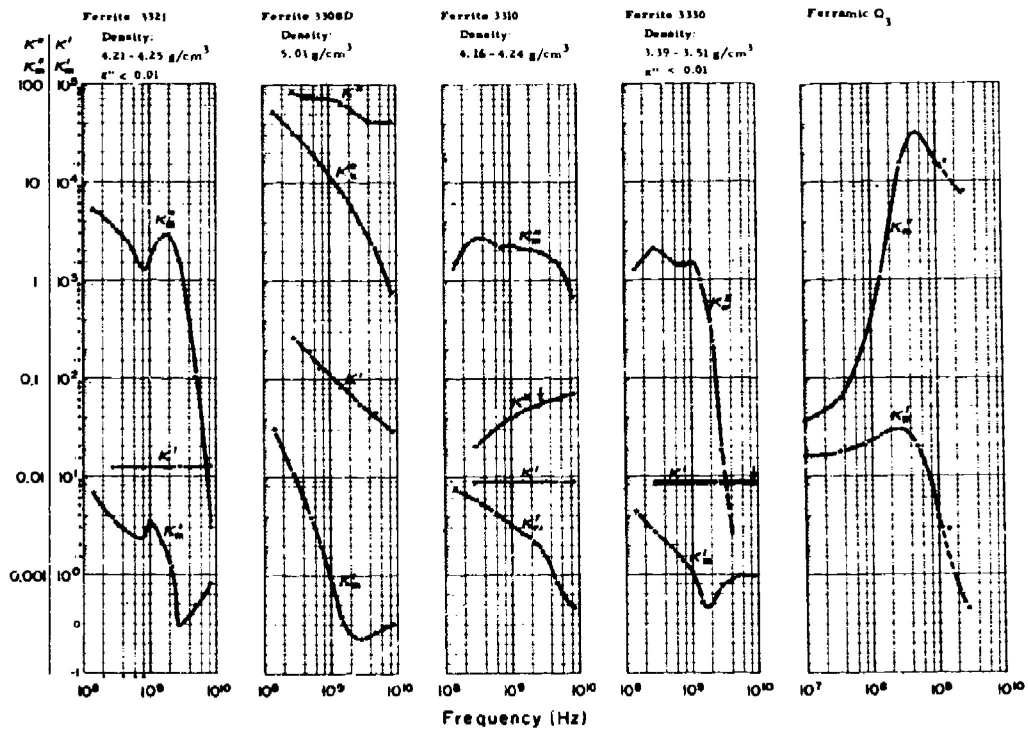
At 8. 52 GHz



CFI 1006

At 25°C

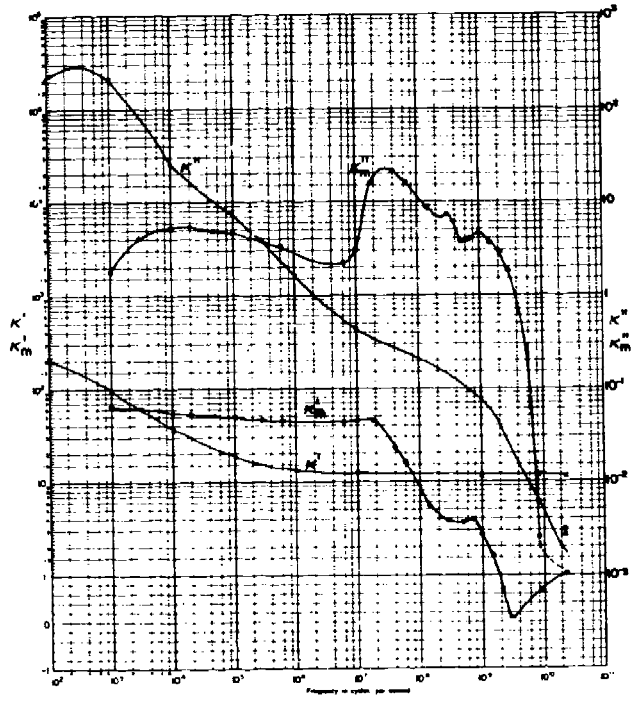



Ferrite 3321
Density:
4.21 - 4.25 g/cm³
ε" < 0.01
Ferrite 3308D
Density:
5.03 g/cm³
Ferrite 3310
Density:
4.16 - 4.24 g/cm³
Ferrite 3330
Density:
3.39 - 3.51 g/cm³
ε" < 0.01
Ferramic Q3
100
10
1
0.1
0.01
0.001
0
-1
Frequency (Hz)

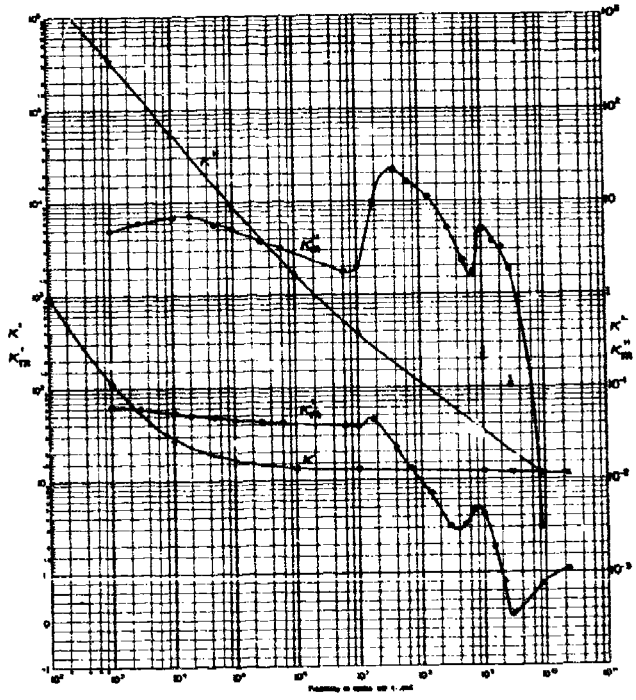
Ferrites (cont.)

General Ceramics
Division of Indiana General

R-1



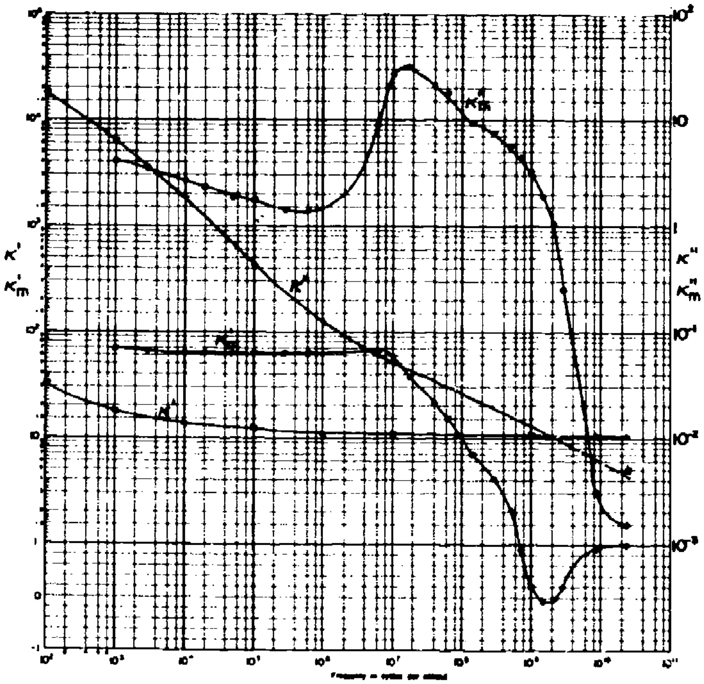
R-4



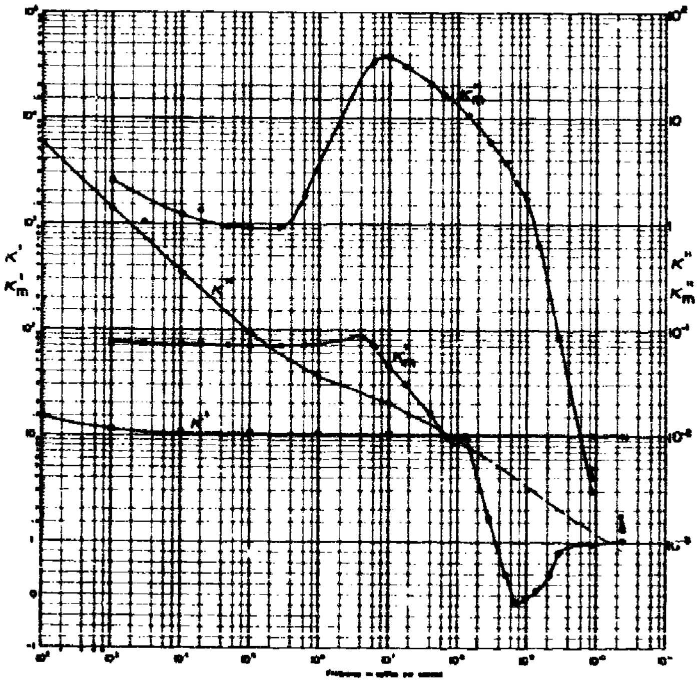
Ferrites (cont.)

General Ceramics
Division of Indiana General

R-5



R-6

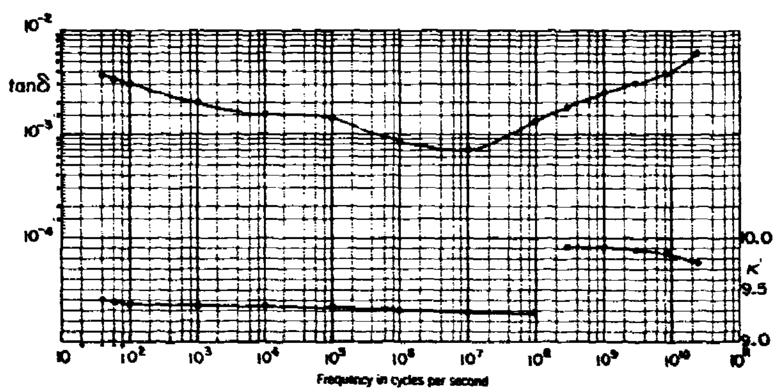


Havelex, glass-bonded mica
At 8.52 GHz, 25°C

Haveg Industries, Inc.
Taunton Division

Type	κ'	tan δ
1080	6.35	.0025
1090	6.17	.0058
1101	8.89	.0027
2101	6.35	.0013
2103	9.2	.0021
2801	6.35	.0020
2803	6.05 - 6.39	.00255 - .0026

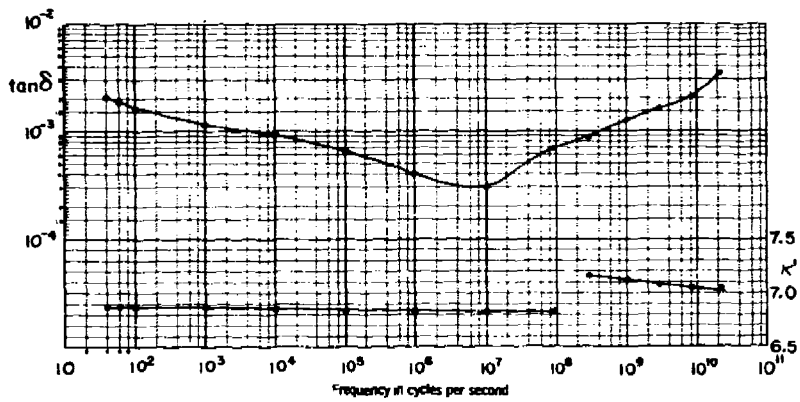
Mycalex 410



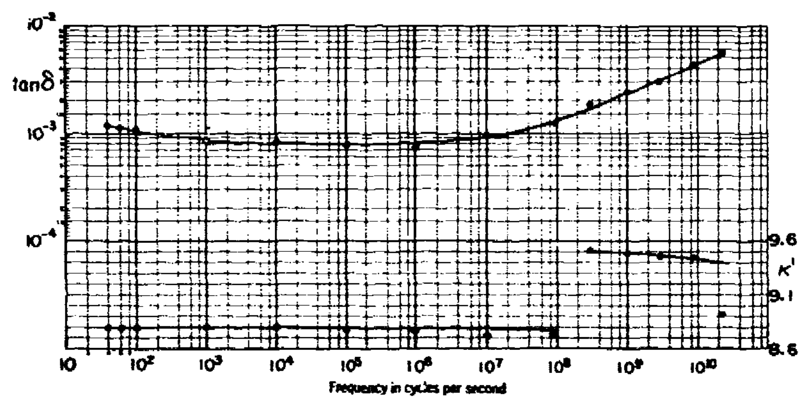
<u>Note</u>: all Mycalex samples from sheet stock. 10^2 through 10^8 Hz, E ⊥ sheet. 3×10^8 to 2.4×10^{10} Hz, E ‖ sheet.

Mycalex (cont.)

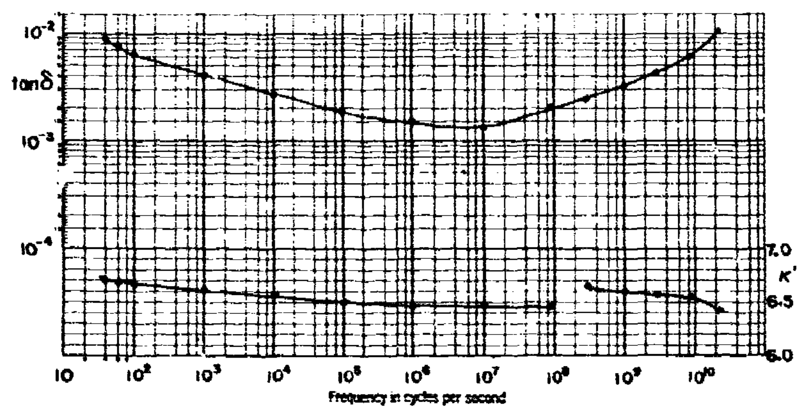
500



555

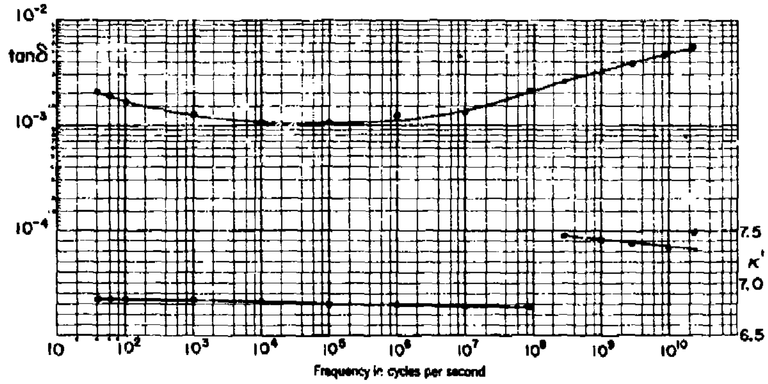


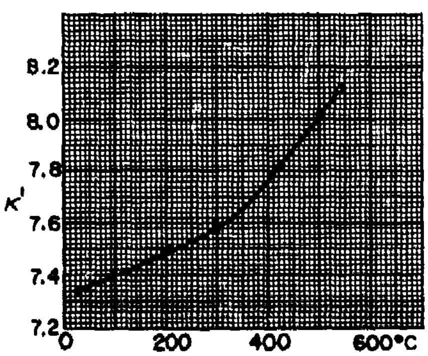
560

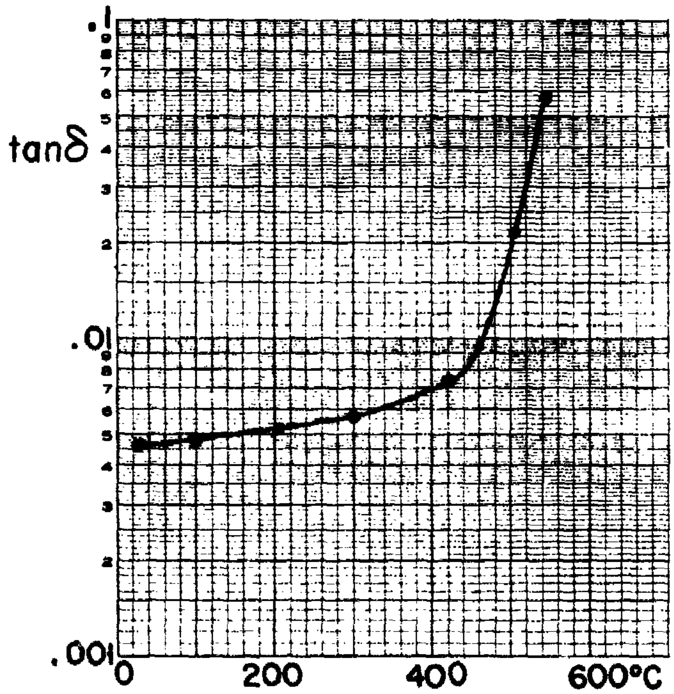


Mycalex (cont.)

620







Miscellaneous Inorganics and .xtures — Raytheon

Asphalt pavement at 40% R.H., 25°C, 14 GHz

Sample No.	Thickness (cm)	Density (g/cm^3)	H_2O (%)	Orientation	κ'	tan δ
1	0.1			Independent	4.73	.0114
2	0.1			"	4.62	.0103
3	0.1				5.03	.0120
4	0.1				5.48	.0095
5	0.91	2.35	.754	Face 1	6.02	.021
				Face 1, 90°	5.53	.052
				Face 2	5.37	.204
				Face 2, 90°	5.44	.102

Concrete pavement at 40% R.H., 25°C, 14 GHz — Raytheon

Sample No.	Thickness (cm)	Density (g/cm^3)	H_2O (%)	Orientation	κ'	tan δ
1	0.1			Various	5.03-5.06	.026-.029
2	0.1			Various	5.06-5.17	.034-.030
3	0.335	2.14	2.21	Face 1	5.21	.059
				Face 1, 90°	5.20	.0612
				Face 2	5.30	.0509
				Face 2, 90°	5.26	.0505
4	0.453	2.04	2.81	Face 1	4.71	.0470
				Face 1, 90°	4.60	.0455
				Face 2	4.70	.0487
				Face ?, 90°	4.55	.0487

Liquid asphalt — Esso

f (Hz)	κ'	tan δ
1×10^9	2.46	.0017
3×10^9	2.46	.0019
8.5×10^9	2.46	.0013

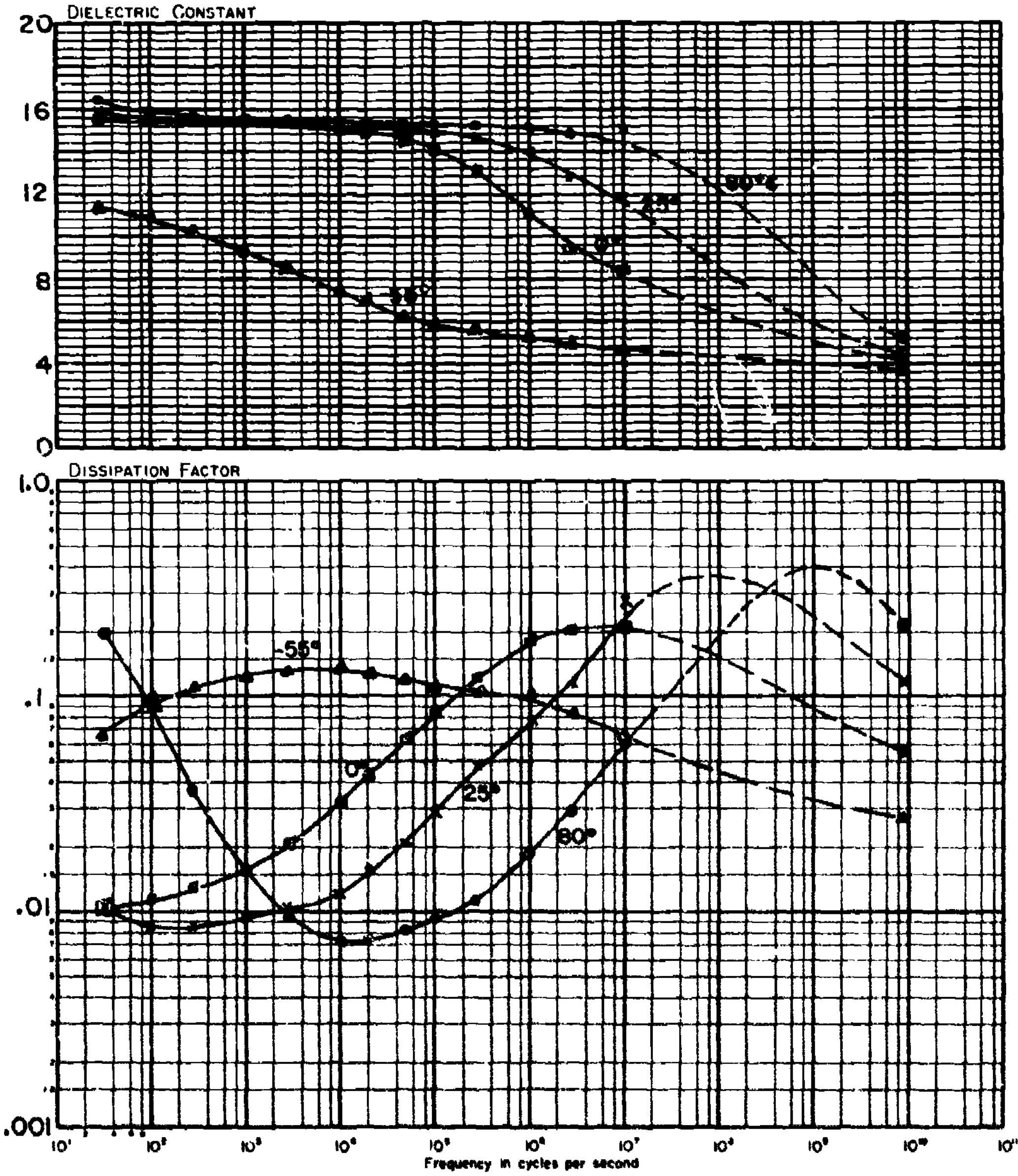
Solid asphalt formed by burning liquid for 2 days at 300°C

f (Hz)	κ'	tan δ
1.5×10^6	2.64	.0043
10^7	2.64	.0030
1.8×10^7	2.64	.0027
4×10^7	2.64	.0025
8.5×10^9	2.63	.0018

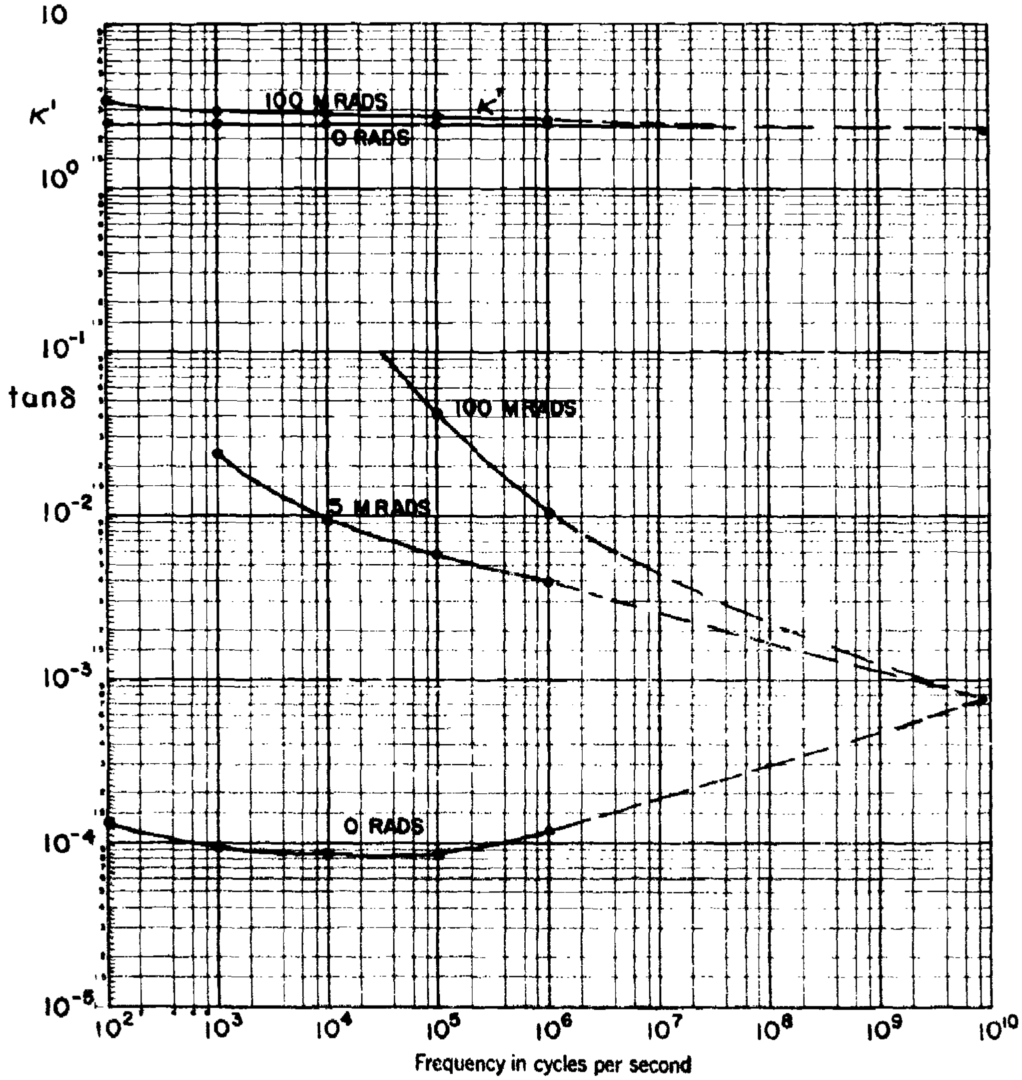
III. ORGANIC COMPOUNDS

(Listed according to supplier)

Cyanoethylated cotton moulding S4403-160-1 — American Cyanamid

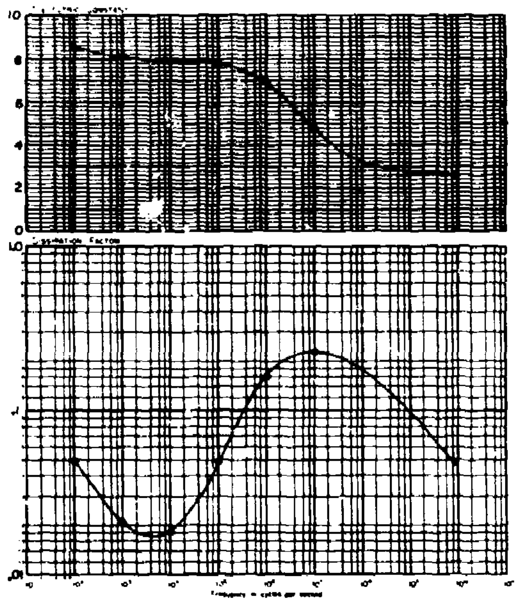


Cymac 325 American Cyanamid
including effect of Van De Graaff irradiation



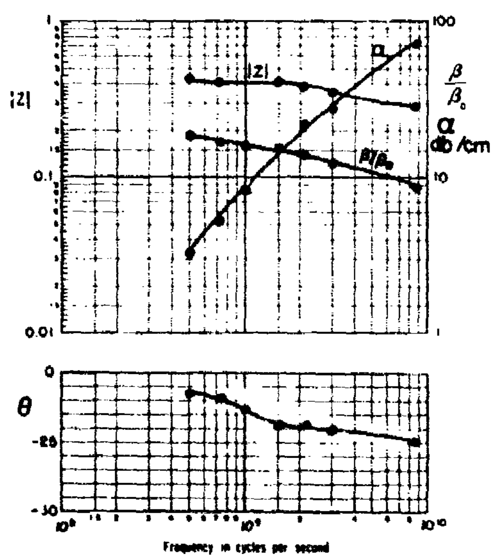
Polyvinylidene fluoride

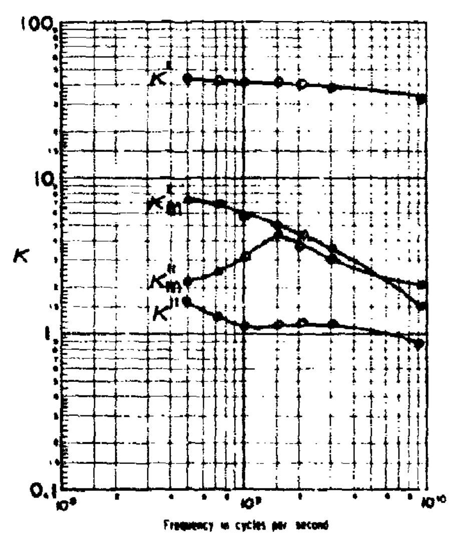
AVCO Research



Polyiron (Carbonyl)

H. I. Crowley





Moulding compound 306 — Dow Corning

	1 GHz		3 GHz			8.52 GHz	
T°C	κ'	tan δ	κ'	tan δ	T°C	κ'	tan δ
25	3.92	.00538	3.87	.00622	-55	3.85	.0060
76	3.91	.0052	3.86	.0058	25	3.84	.0067
103	3.90	.0052	3.85	.0058	61	3.835	.00655
129	3.89	.0051	3.84	.0056	118	3.825	.0064
150	3.87	.0050	3.83	.0055	147	3.82	.00635
216	3.83	.0050	3.78	.0051	199	3.807	.00625
255	3.80	.0052	3.75	.0051	315	3.74	.00615
305	3.77	.0056	3.72	.0054	400	3.66	.0061
410	3.68	.0064	3.63	.0068	499	3.57	.0060
504	3.62	.0058	3.58	.0066	296	3.72	.0061
301	3.75	.0048					

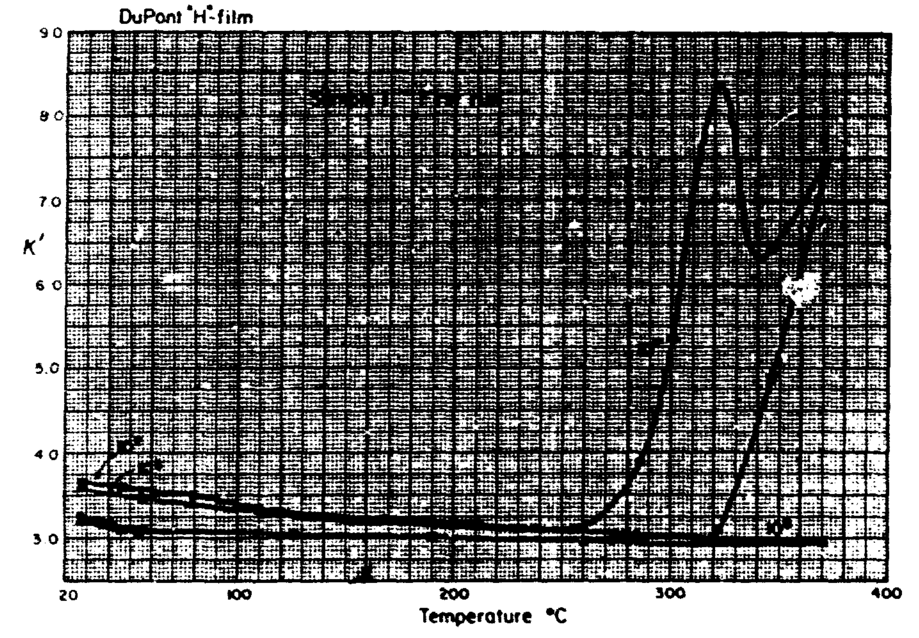
	T°C		1000 MHz	3000 MHz	8500 MHz
Silastic RTV 501	-55	κ'	3.17	3.07	
		tan δ	0.025	0.037	
	23	κ'	2.89	2.88	2.87
		tan δ	0.0053	0.0104	0.0175
	150	κ'	2.62	2.62	
		tan δ	0.042	0.0045	
RTV 521	23	κ'	3.33	3.32	3.31
		tan δ	0.0086	0.0153	0.0252
RTV 1602	-55	κ'	3.09	3.03	
		tan δ	0.0220	0.0308	
	23	κ'	2.93	2.92	2.91
		tan δ	0.0073	0.0117	0.0187
	150	κ'	2.77	2.75	
		tan δ	0.0044	0.0060	
RTV 5350	-55	κ'	3.22	3.14	
		tan δ	0.0234	0.0287	
	23	κ'	3.06	3.05	3.04
		tan δ	0.0043	0.0088	0.0166
	150	κ'	2.82	2.79	
		tan δ	0.0040	0.0043	
S-6538	-55	κ'	3.01	2.96	
		tan δ	0.0242	0.0260	
	23	κ'	2.99	2.98	2.97
		tan δ	0.0069	0.0124	0.0187
	150	κ'	2.78	2.77	
		tan δ	0.0039	0.0047	
Sylgard 182	-55	κ'	2.90	2.86	2.81
		tan δ	0.0200	0.024	0.029
	23	κ'	2.79	2.77	2.73
		tan δ	0.0081	0.0120	0.0199
	150	κ'	2.50	2.48	2.45
		tan δ	0.0026	0.0040	0.0073

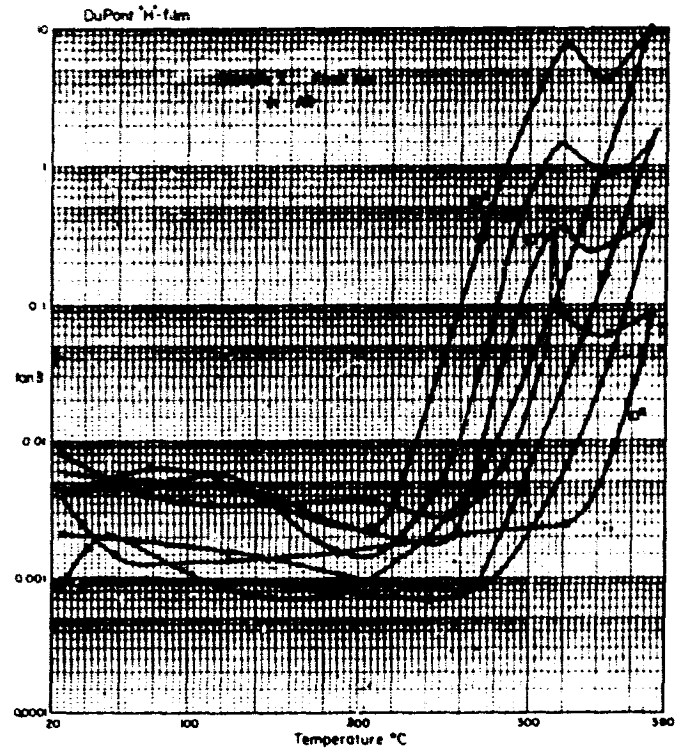
DC-92.007

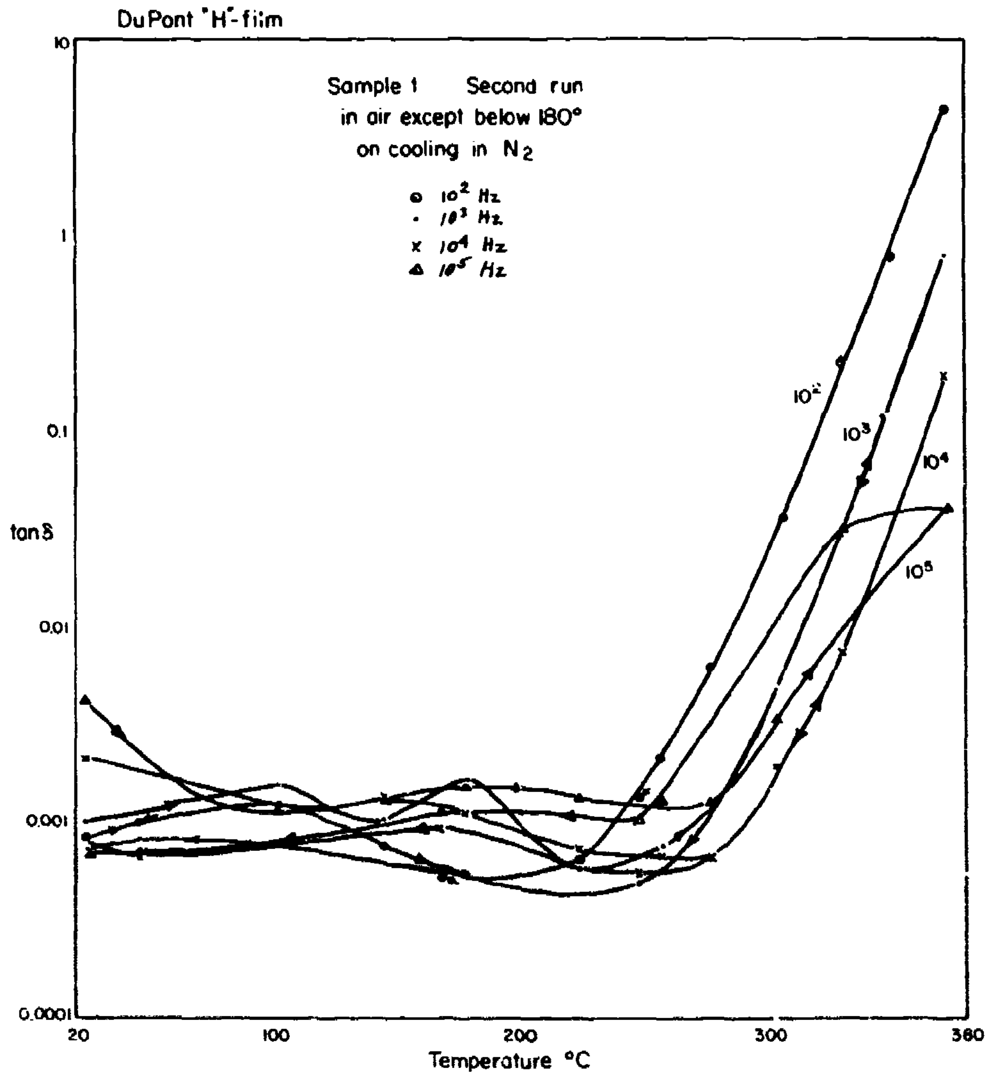
8.52 GHz, 25°C, 50% R.H., κ' = 4.92; tan δ = 0.091

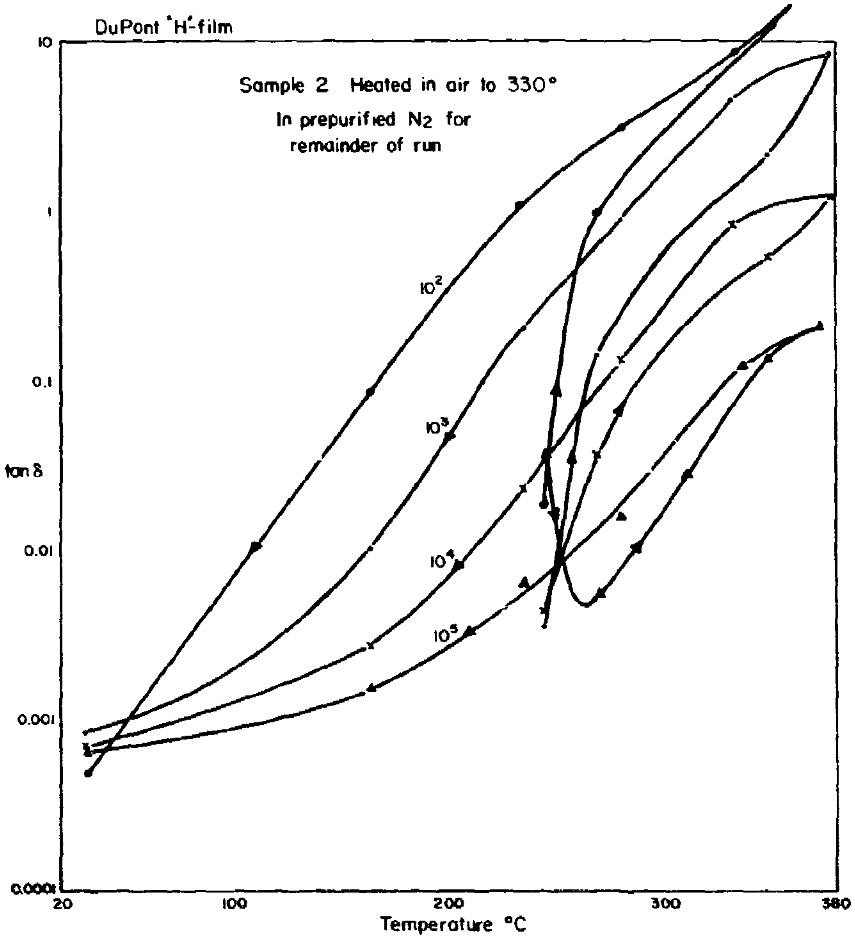
"H"-film

E.I. Dupont de Nemours and Co.






DuPont "H"-film
Sample 1 Second run
in air except below 180°
on cooling in N2
10² Hz
10³ Hz
10⁴ Hz
10⁵ Hz
10
1
0.1
0.01
0.001
0.0001
tan δ
20
100
200
300
360
Temperature °C

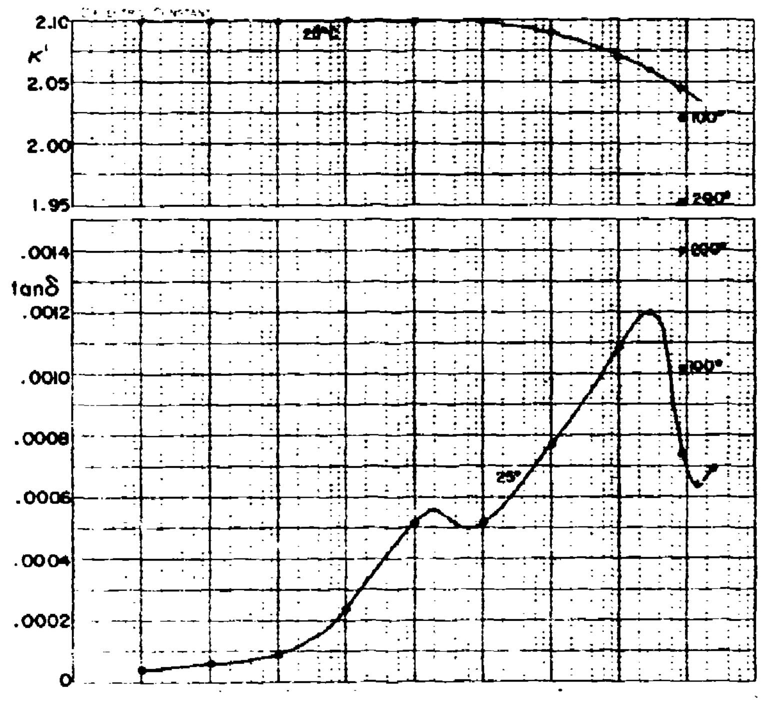


Teflon FEP (1963)

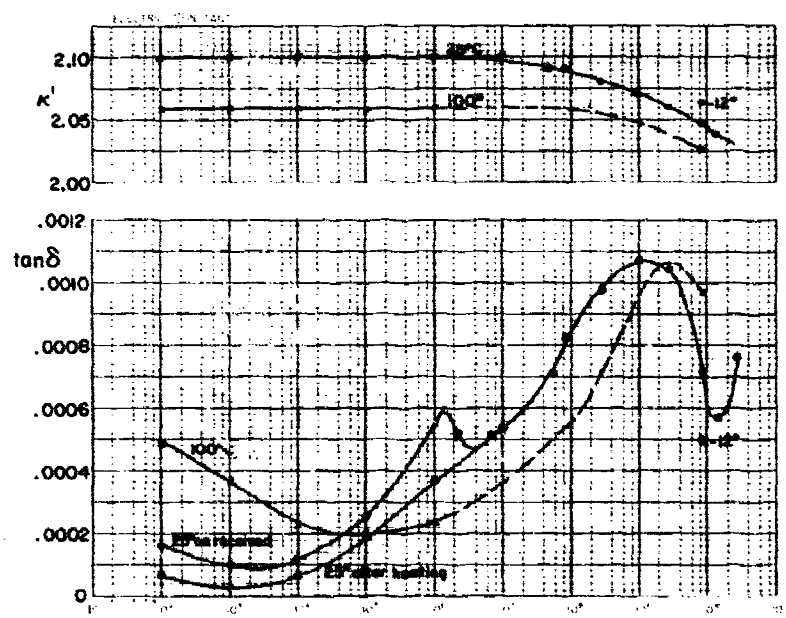
Density = 2.153 g/cm^3, at 25°C, 8.52 GHz

κ' = 2.058, tan δ = 0.00108

Teflon FEP (1964) E. I. Dupont de Nemours and Co.

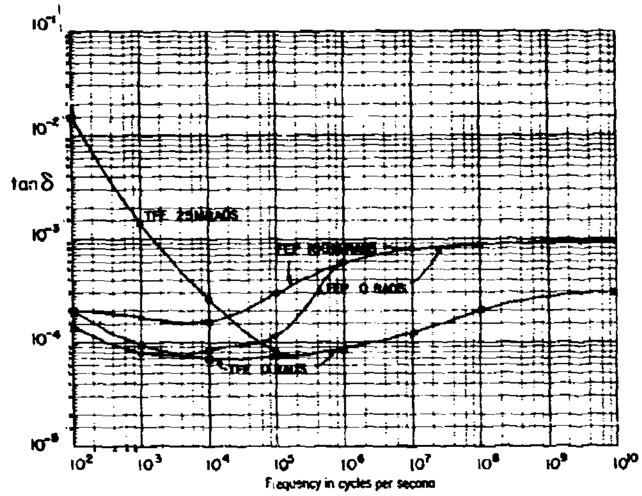


Teflon 9033, Lot 10601, density at 25°C = 2.147, similar for
Teflon T-100, Lot 38180, " " " = 2.152

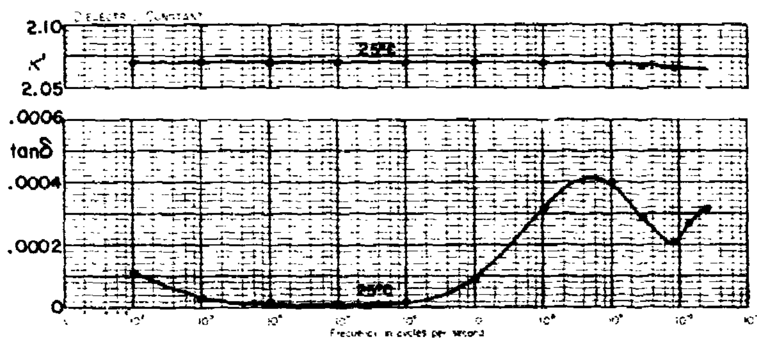


Teflon 100X (FEP) 1960 and TFE E. I. Dupont de Nemours and Co.

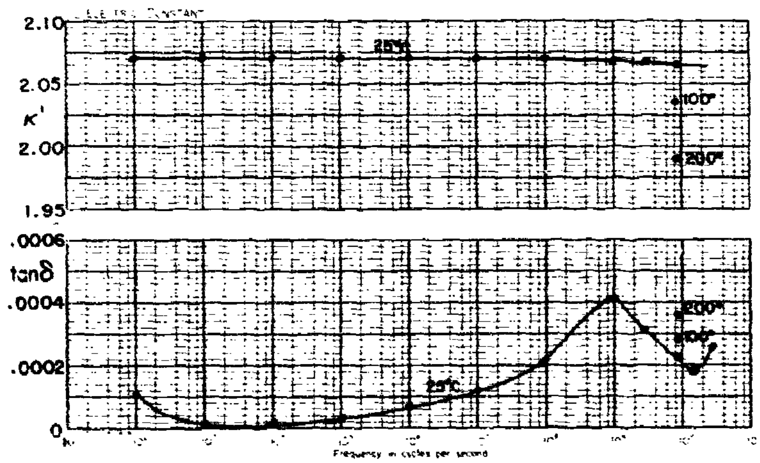
Effect of Van De Graaff irradiation, 25°C



TFE-7 (1964)



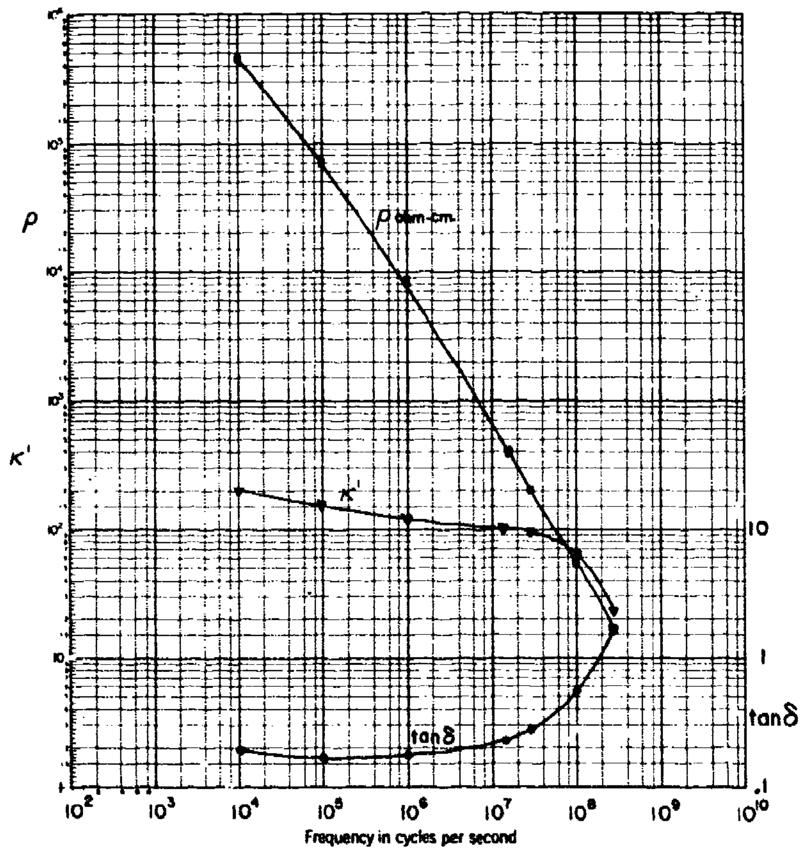
TFE-6C (1964)



"Polyguide" Electronized Chemicals Corp.

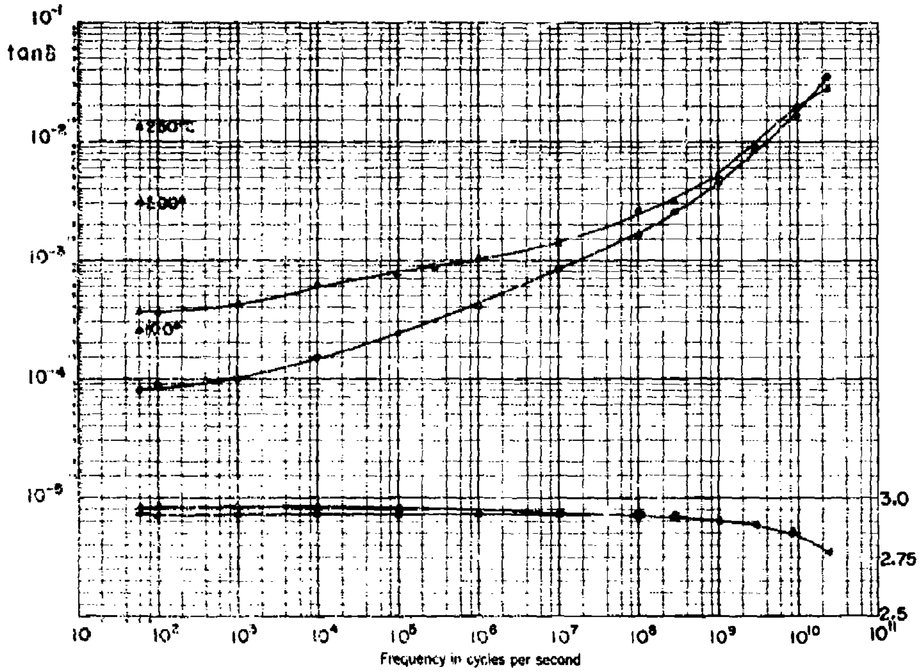
		3 GHz		8.52 GHz		% wt.
		κ'	tan δ	κ'	tan δ	increase
As received	25°C	2.32	.00034	2.319	.00030	
	-48°C			2.320	.00017	
	74°C			2.300	.00040	
After 24 hrs. H_2O		2.32	.00047	2.320	.00038	.007

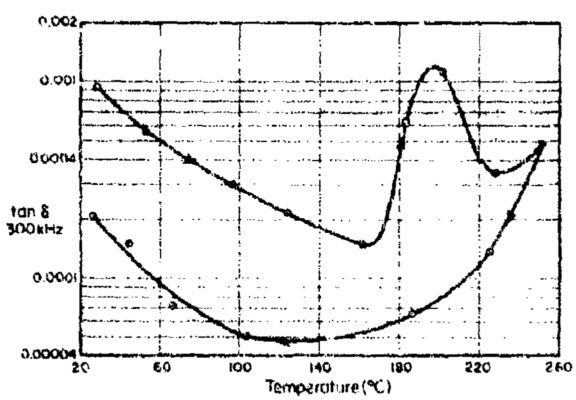
Emerson and Cumming A-19
graphite fiber loaded plastic, November 1966



SE 900 Silicone Rubber — General Electric

Δ Sample cured 1 hr at 300°F, measured at 50% R. H.
○ Normal cure





Lexan — General Electric

f(Hz)	κ'	tan δ
8.5×10^9	2.77	.00615
2.5×10^{10}	2.75	.00593

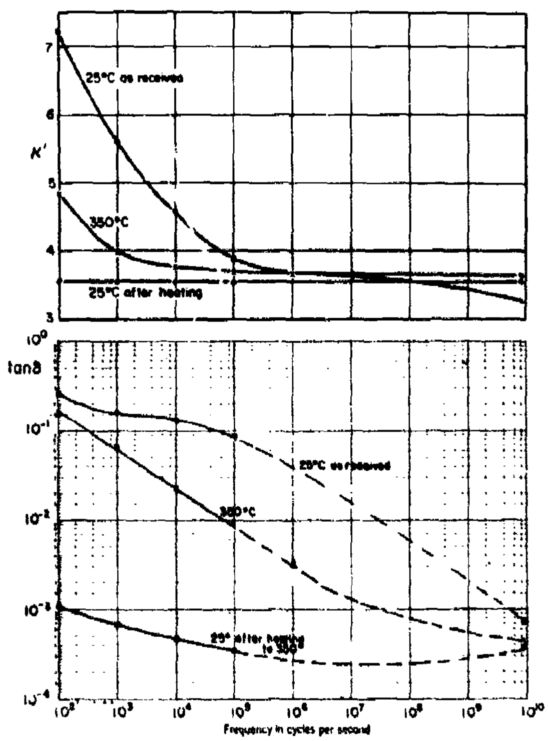
"3M" board — Minnesota Mining and Metallurgy

		3 GHz		8.52 GHz		% wt. increase
		κ'	tan δ	κ'	tan δ	
As received	25°C	2.32	.00038	2.316	.00037	
	-48°C			2.316	.00015	
	74°C			2.300	.00040	
After 24 hrs H_2O	25°C	2.32	.00060	2.316	.00043	

Polyurethane rigid foam, at 399 MHz — Nopco Chemical Corp.

	3.80 lbs/cu. ft		7.54 lbs/cu. ft	
T°F	κ'	tan δ	κ'	tan δ
77	1.087	.00136	1.165	.00242
116	1.088	.00176	1.170	.00276
164	1.093	.00208	1.175	.00344

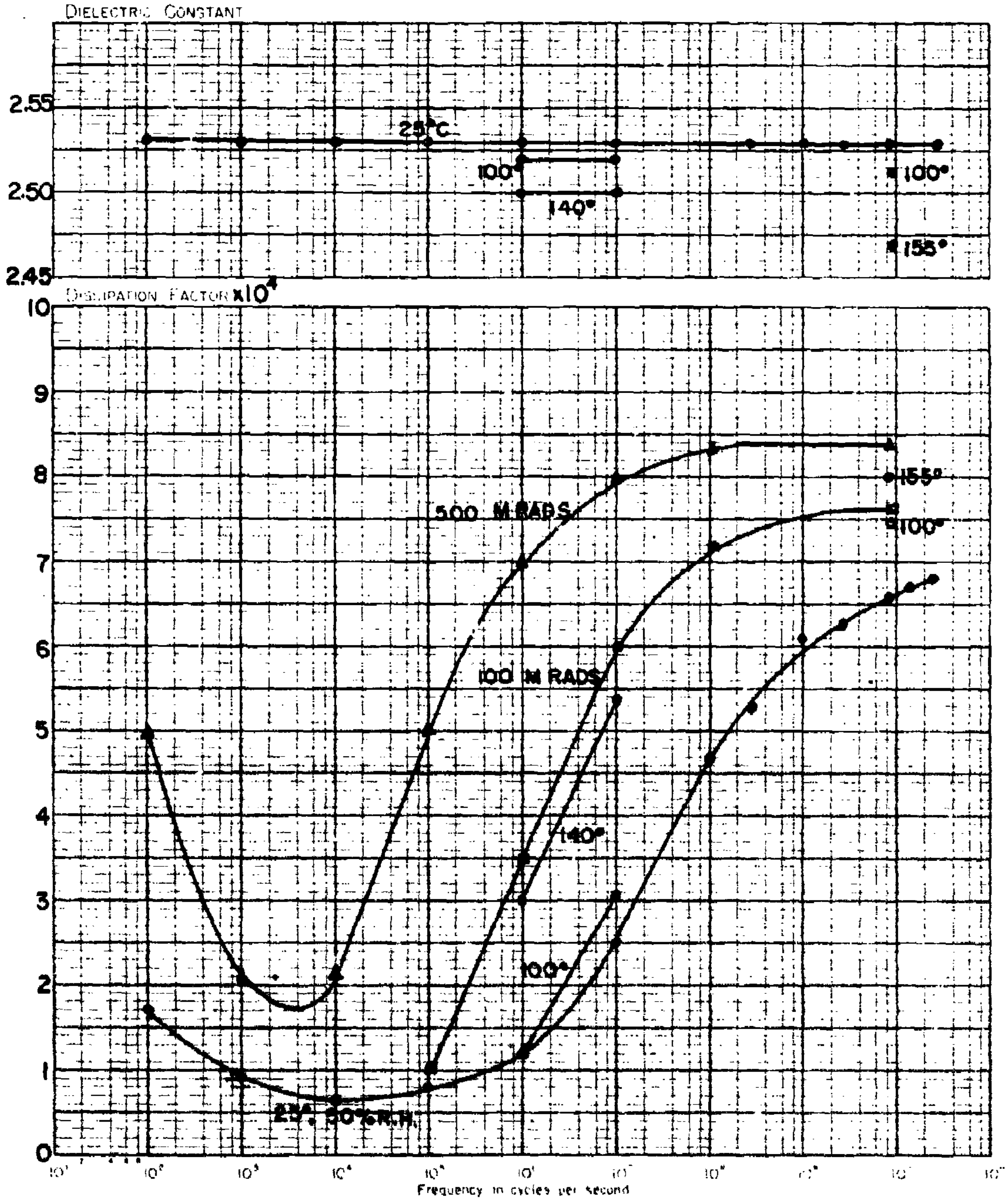
Fluorosint (1960) — Polymer Corp.



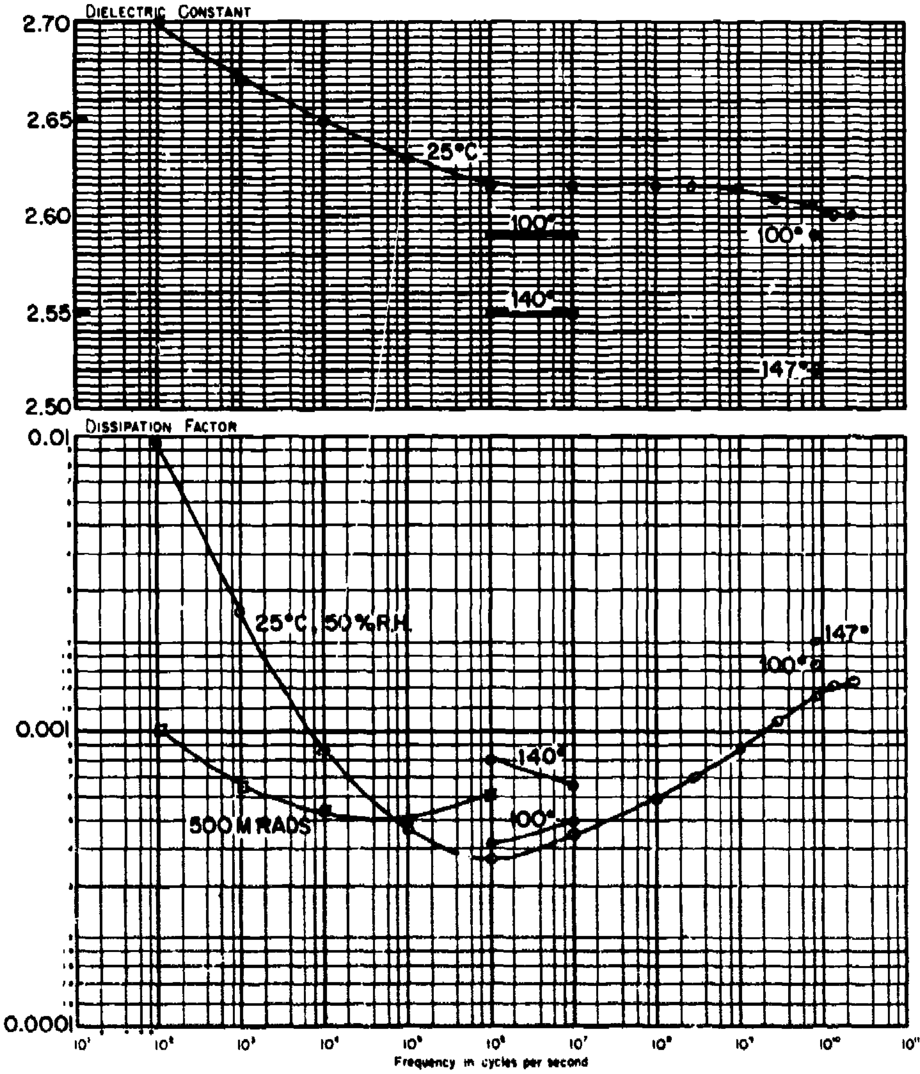
Wm. Brand Rex Division
of American Enka Corp.

Rexolite 1422 (1964),

including effect of Van De Graaff irradiation (1960)



Rexolite 2200 (1964),
including effect of Van De Graaff irradiation (1960)

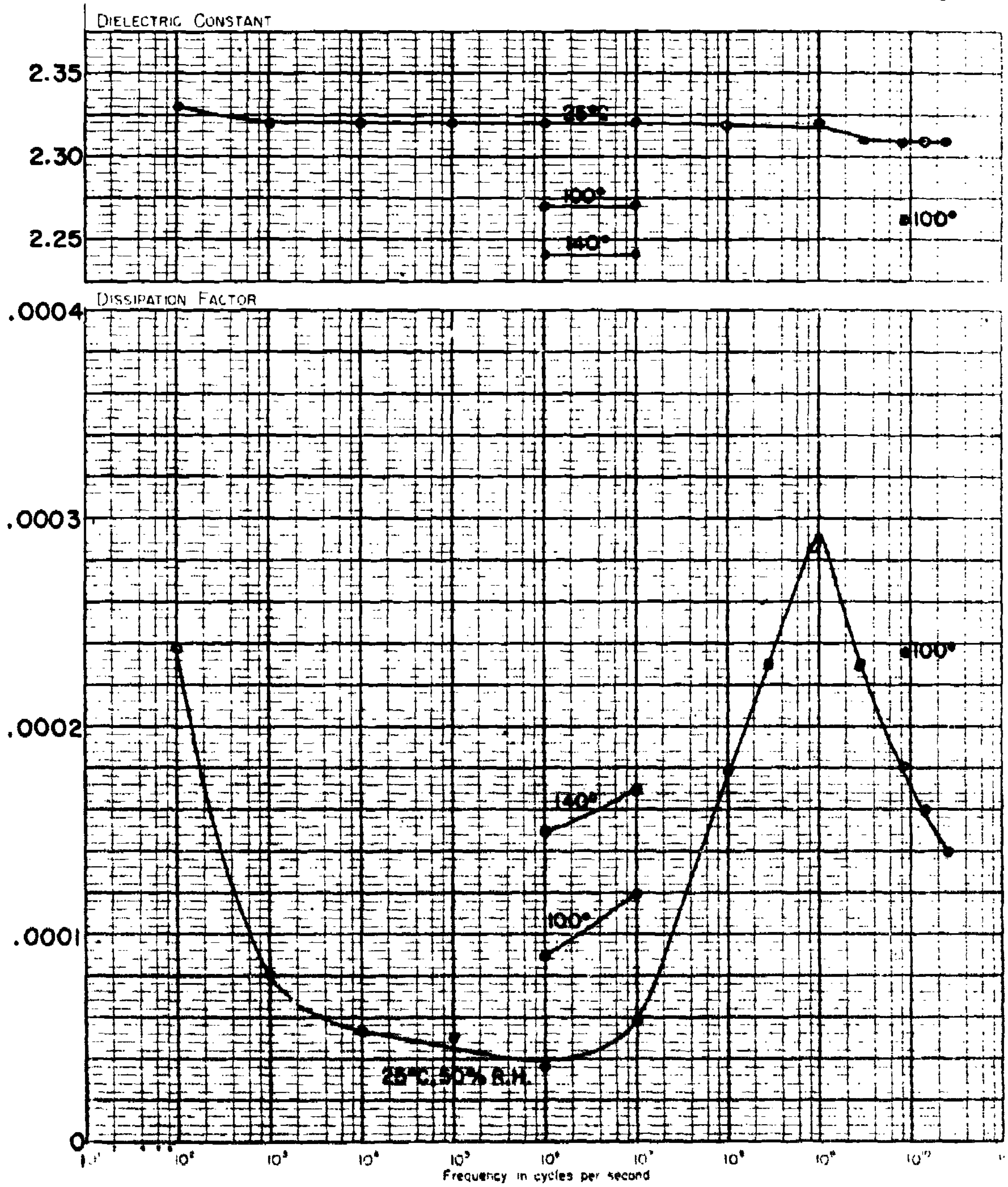


Rexolite 2200 (1965)

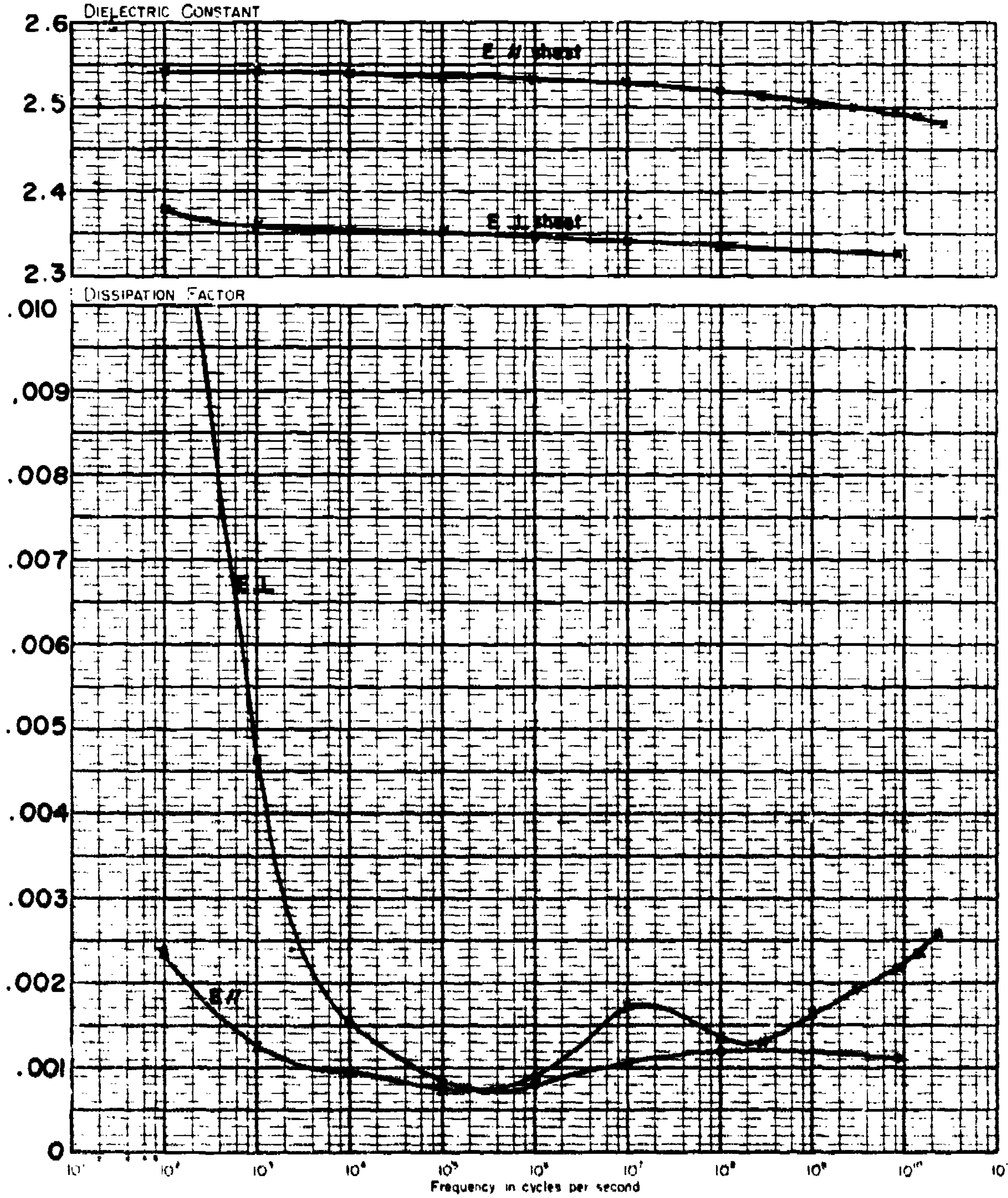
		3 GHz		8.52 GHz		% wt. increase
		κ'	tan δ	κ'	tan δ	
As received	25°C	2.65	.00169	2.65	.00170	
	-48°C			2.64	.00110	
	74°C			2.645	.00209	
After 24 hrs. H_2O	25°C	2.66	.0026	2.66	.00343	.055

Rexolene P

Wm. Brand Rex Division
of American Enka Corp.



Duroid 5870 (1966) Rogers Corp.



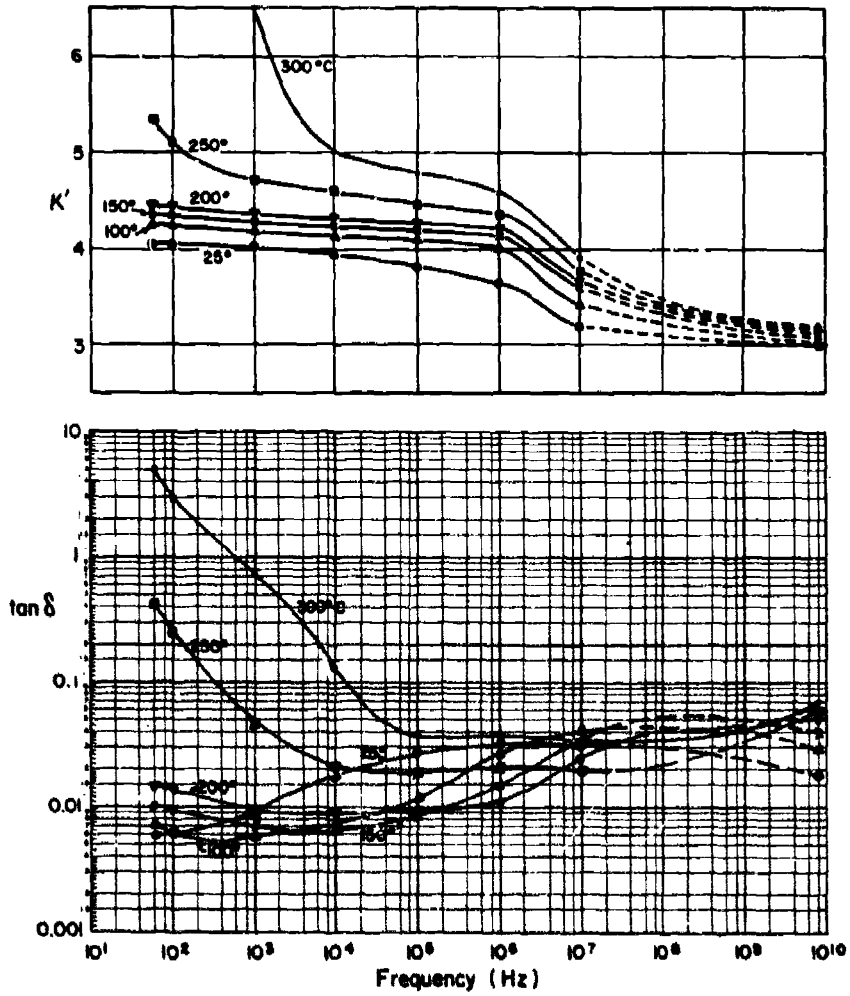
Epon 828/PMDA casting

Shell Chemical Company

156 pts. { Epon 828 epoxy 100 pts. by weight
PMDA (pyromellitic dianhydride) 56 pts. by weight

plus

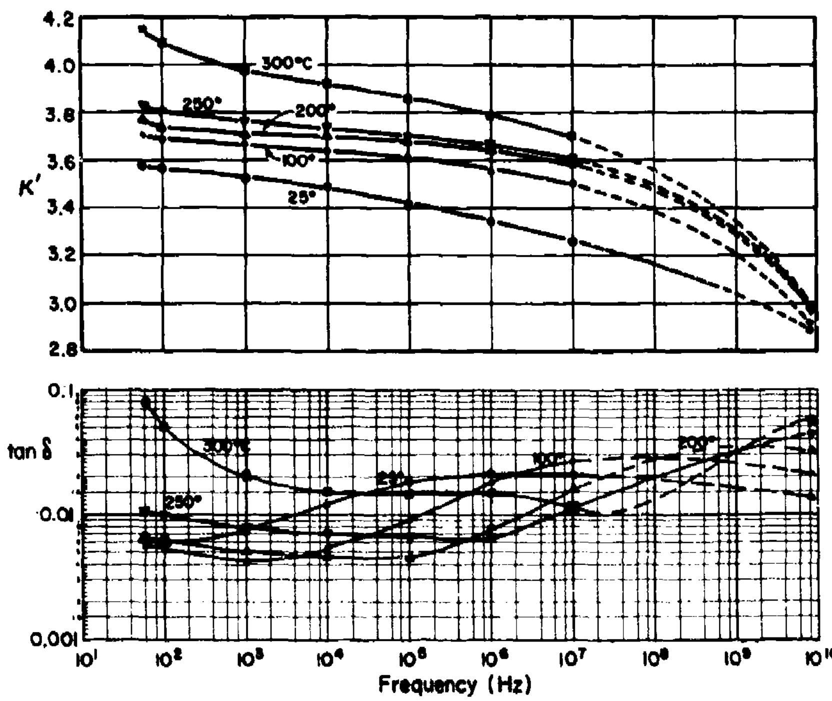
20 pts. { Tetrahydrofurfural alcohol 99 pts. by weight
Dicyandiamide 1 pt. by weight



Epon 828/PMDA casting — Shell Chemical Company

Epon 828 epoxy 100 pts. by weight

PMDA (pyromellitic dianhydride) 31 pts. by weight

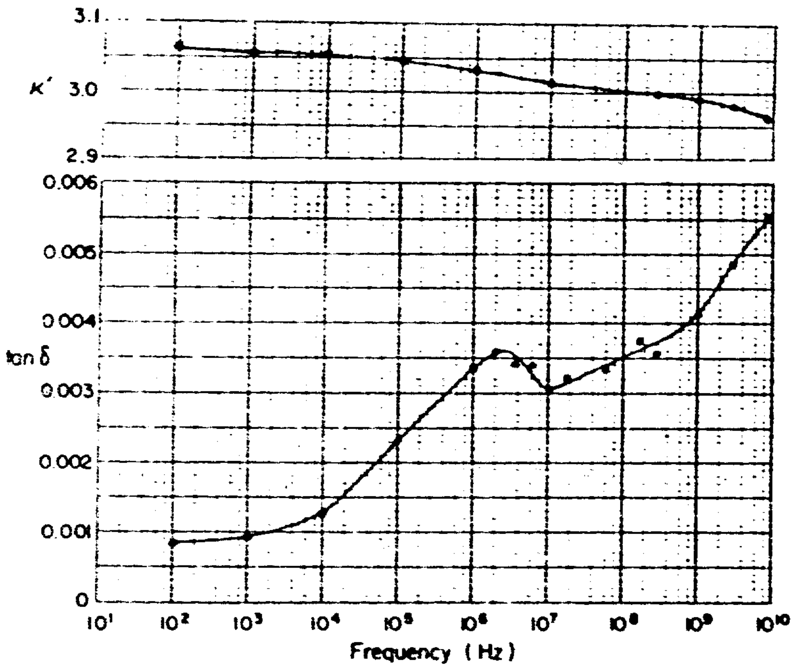


Tellite 3A — Tellite Corp.

	T°C	κ'	tan δ	κ'	tan δ	% weight increase
As received	25	2.31	.00028	2.311	.00022	
	-48			2.318	.00020	
	74			2.294	.00027	
After 24 hrs H_2O	25	2.31	.00036	2.311	.00032	.003

Polysulfone, 25°C, 50% R.H.

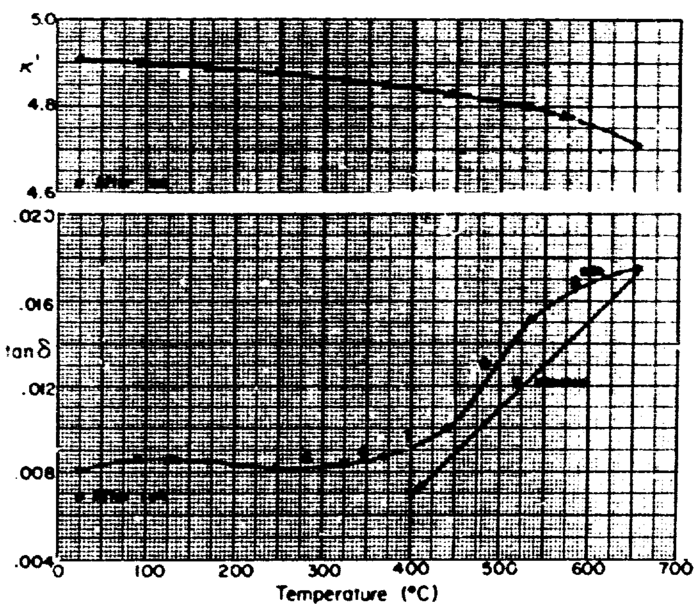
Union Carbide Corp.
Plastics Division

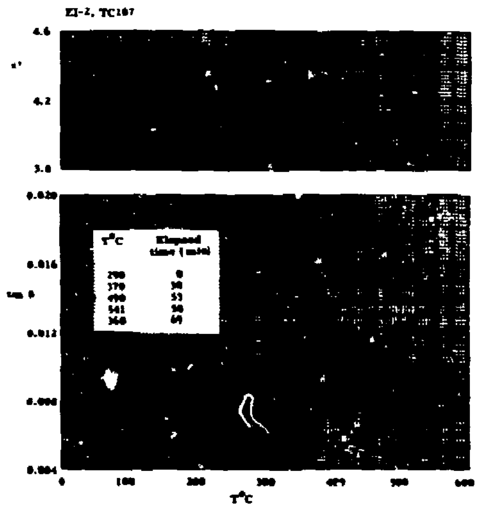


Fiberglass laminate

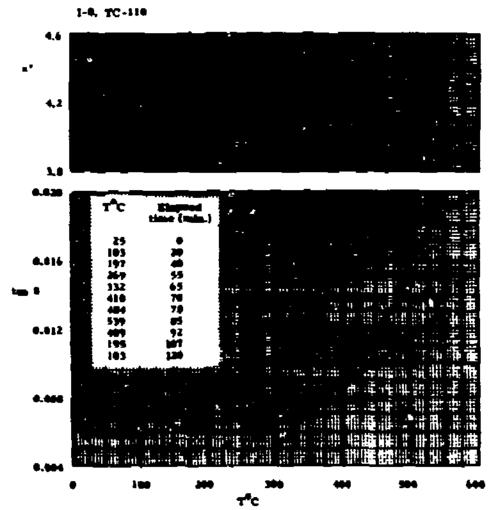
Air Force Materials Laboratory

with polybenzimidazole resin (approx. 24%)
density 1.949 g/cm^3

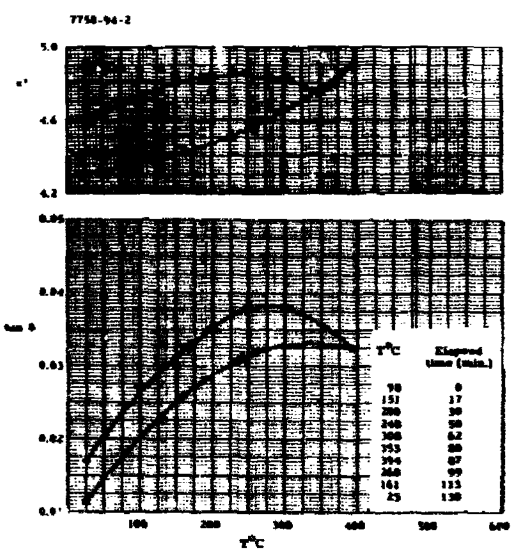




Fiberglass laminate with 181 glass cloth and a polyol cross-linked polyimide resin, 8. 52 GHz



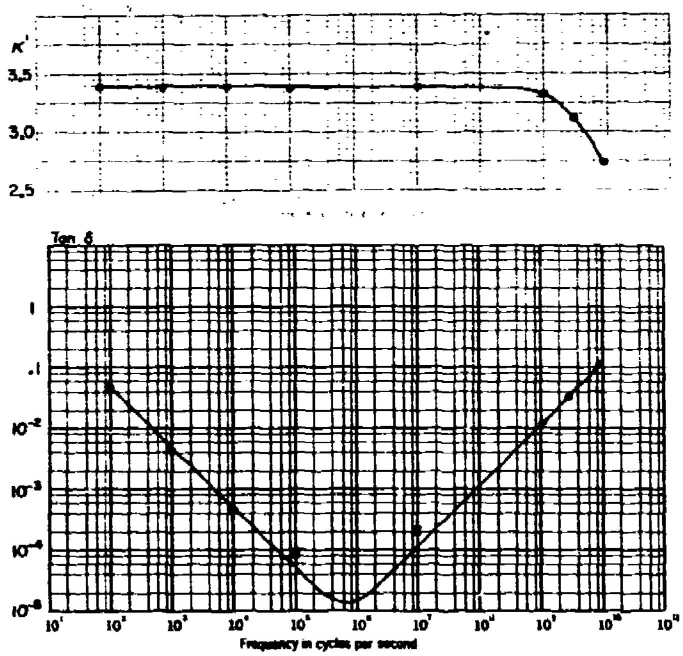
Fiberglass laminate with 181 glass cloth and a polyimide resin, 8. 52 GHz



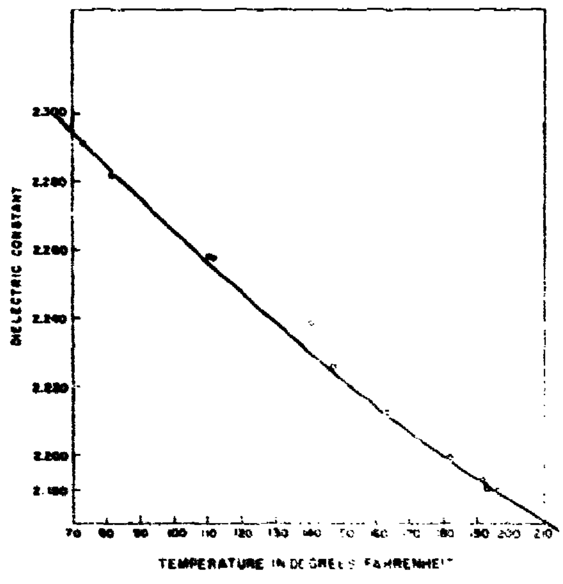
I lass laminate with 181 glass cloth ...d epoxy resin, 8. 52 GHz

IV. LIQUIDS

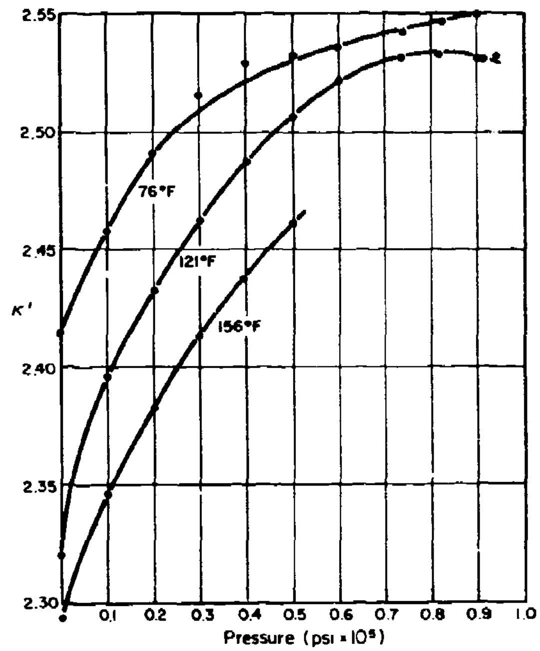
Dowtherm A — Dow Chemical

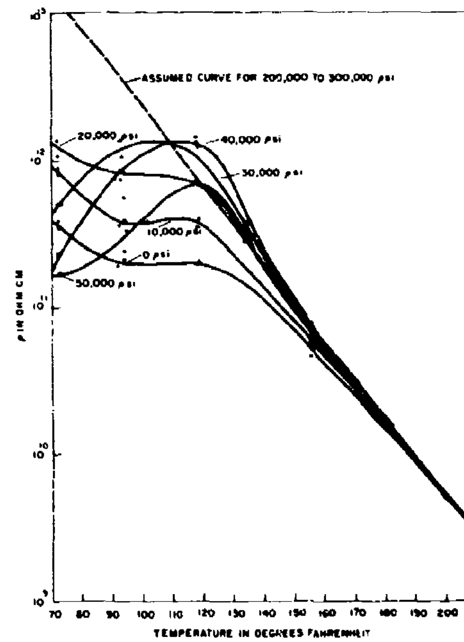


Teresso V-78 — Esso



Teresso V-78 (cont.)



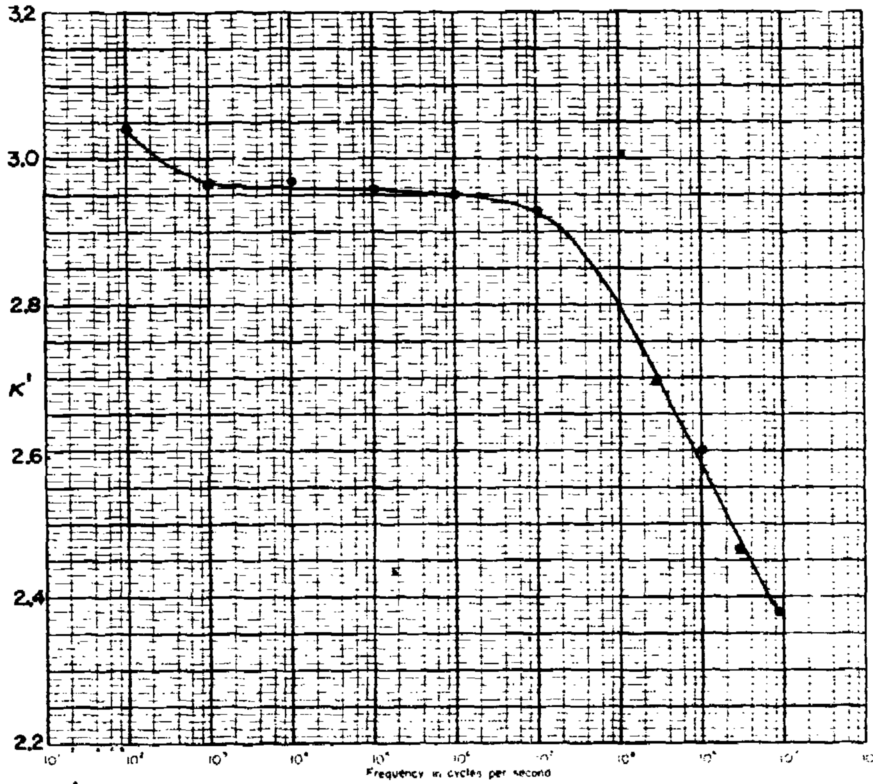


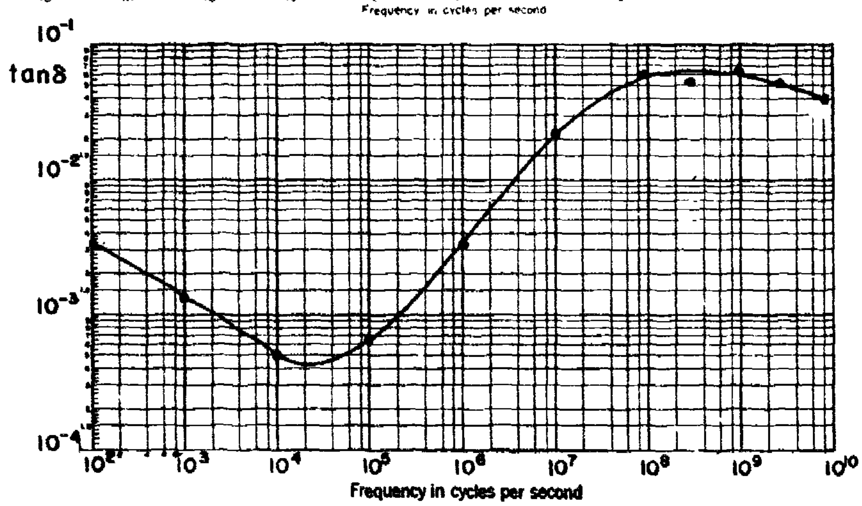
pressure

temperature

V. FOODSTUFFS

Kremax Armour





Frozen lean steak

$T^{o}F$	150 MHz κ	150 MHz tan δ	1000 MHz κ	1000 MHz tan δ	3000 MHz κ	3000 MHz tan δ
-75	3.42	.022	3.33	.0164	3.22	.0105
-60	3.61	.040	3.42	.026	3.40	.014
-50	3.70	.058	3.46	.036	3.44	.0185
-40	3.82	.072	3.51	.050	3.46	.024
-30	3.92	.094	3.60	.066	3.55	.032
-20	4.18	.102	3.80	.089	3.70	.040
-10	4.50	.138	4.10	.12	3.80	.054
0	5.33	.18	4.40	.165	3.95	.076
10	6.35	.24	5.18	.223	4.37	.108
20	9.55	.39	9.50	.203	7.30	.174
30	33	.60	20.8	.254	8.40	.250
40	53.5	.22	33.0	.32	8.30	.208
50	53.0	.21				

Vacuum-dry lean beef

$T^{o}F$	150 MHz κ	150 MHz tan δ	1000 MHz κ	1000 MHz tan δ	3000 MHz κ	3000 MHz tan δ
-60			1.495	.00320	1.471	.00335
-40	1.535	.0060	1.497	.00375	1.473	.00395
-20	1.548	.0080	1.502	.00436	1.475	.0047
0	1.562	.0102	1.511	.00535	1.480	.0057
20	1.582	.0132	1.520	.0066	1.483	.0068
40	1.60	.0168	1.530	.0080	1.490	.0082
60	1.62	.0216	1.542	.0096	1.500	.0099
80	1.648	.0264	1.558	.0111	1.509	.0119
100			1.571	.0127	1.522	.0138
120			1.587	.0143	1.535	.0147
140			1.604	.0160	1.545	.0175
160			1.622	.0176	1.560	.0193
180			1.642	.0198	1.590	.0214

Potato (Maine, 78.9% H_2O), 25°C

f (GHz)	κ'	tan δ
.3	130	.83
1	87	.39
3	81	.38

Potato flakes, density 0.284

f (GHz)	κ'	tan δ
.3	1.50	.034
1	1.485	.030
3	1.47	.029

Potato chips

	f (GHz)	κ'	tan δ
partly cooked	1	5.76	.36
	3	5.18	.55
cooked	1	1.89	.034
	3	1.86	.036

f (Hz)	Nescafe κ'	tan δ	σ	Nestea κ'	tan δ	σ
10^2	1.557	.0115	9.93×10^{-13}	1.290	.00442	3.17×10^{-13}
10^3	1.529	.0113	9.58×10^{-12}	1.281	.00384	2.73×10^{-12}
10^4	1.490	.0103	8.52×10^{-11}	1.276	.00301	2.13×10^{-11}
10^5	1.488	.0090	7.43×10^{-10}	1.270	.00245	1.73×10^{-10}
10^6	1.471	.0089	7.27×10^{-9}	1.267	.00230	1.62×10^{-9}
10^7	1.453	.0093	7.52×10^{-8}	1.260	.00196	1.37×10^{-8}
3×10^8	1.432	.0106	2.53×10^{-7}	1.24	.0023	4.75×10^{-7}
10^9	1.39	.0098	7.57×10^{-6}	1.22	.0024	1.63×10^{-7}
3×10^9	1.36	.0093	2.11×10^{-5}	1.21	.0026	5.25×10^{-6}
8.5×10^9	1.34	.0086	5.65×10^{-5}	1.20	.0033	1.87×10^{-5}
	density 0.241 g/cm^3				0.126 g/cm^3	

Eggwhite

Frequency	κ'	tan δ	ρ
3×10^9	35	.5	
9.2×10^9	13	1.1	
10^4, 10^5			35

Bread

1.2×10^7	11	3.35	

Dough

10^7	2×10^5	2.25	1

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	2b. GROUP

3. REPORT TITLE
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4. DESCRIPTIVE NOTES (Type of report and inclusive dates)
Technical Report

5. AUTHOR(S) (Last name, first name, initial)
Iglesias, J., and Westphal, W. B.

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Office of Naval Research and Air Force Materials Laboratory

13. ABSTRACT

This is a summary report on dielectric constant and loss measurements made in this laboratory after 1958, excepting high-dielectric-constant materials. The emphasis is on high-temperature materials (those with melting points above 1200°C), but data on some plastics and liquids are also included. The samples of solids include oxides of Al, Be, Cr, Hf, Mg, Si, Ta, Th, Y, Zr, nitrides of B and Si, $LaAlO_3$ and various silicates, rocks, and minerals. Pure samples of Al_2O_3, BeO, MgO, SiO_2, and BN all show loss tangents < 0.01 at 1500°C in the microwave region. Various phenomena of electric loss, e.g., transconductance, dipole orientation, and molecular vibrations are clearly discernible.

DD FORM 1 JAN 64 1473

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Security Classification

Unclassified

Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Dielectric constants Dielectric losses Dielectric properties of geophysical materials, foods, high-temperature inorganics						

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